Laboratory Studies of Gas Permeability of Frozen Soil

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ABSTRACT

A preliminary investigation on the gas permeability of frozen soil was conducted in this study. A unique low-temperature permeability testing system was designed and developed. Widely accepted standard procedures were followed to prepare soil samples. A number of experiments were conducted in a cold chamber with controlled temperature. The impact of several parameters upon the gas permeability of frozen soil was investigated. The experiment results indicated that among the parameters examined, moisture content had the most significant impact on the gas permeability of frozen soil and the effect of temperature was less significant than that of moisture content. It was also found that there seemed to be a transition zone around 10% of moisture content. With moisture content above this level, the permeability was less sensitive to temperature change, while below this level the permeability was more sensitive to temperature change. Another finding was that the permeability increased when the temperature fell below 20°F. In addition, applying loads decreased permeability by 10% to 30% dependent on the setting of other parameters. Some suggestions for improvement of the experiments and future research works were also presented.

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Chapter 1

Introduction

1.1 Gas Pipeline in Alaska

Population growth and economic development in the world have led to the increased use of natural gas. In the late 1970s and early 1980s, there were intense discussions about the construction of a natural gas pipeline from Prudhoe Bay, Alaska to Alberta and points south. The 1976 Alaska Natural Gas Transportation Act calls for the pipeline to follow the Alaska Highway over the Canadian Rockies into Alberta, where it could split to supply West Coast and Midwest. It was commonly referred to as the Foothills Project. In May 1977, an alternate proposal, supported by the government of Canadian Northwest Territories, would put the initial stages of the pipeline under the Beaufort Sea off Canada's north coast. Once it reached the mouth of the Mackenzie River, the pipeline would follow the river valley into Alberta. Alaska Highway Gas Pipeline (AHPP) Project was postponed in mid-1980 because of falling energy price. Foothills Pipe Lines Ltd constructed a portion of the gas pipeline, now known as the "Pre-build" pipeline or Phase I of the Alaska Highway Pipeline Project during that period of time. However, gas has become the fuel of choice and demand is expected to rise by 30 percent by the end of the decade. Particularly since the September 11 attacks, a proposed natural gas pipeline from Alaska through Canada and into the continental United States is more important than ever for national energy security. Therefore, the factors mentioned above have all come together to heighten interest in delivering natural gas to market from Prudhoe Bay.

However, a successful means to deliver natural gas from gas reservoirs in the far north regions to consumers requires a careful execution of a multi-billion dollars task that involves many aspects of economic, engineering, and environmental studies. One of the potential environmental problems when constructing a gas pipeline in Arctic and Sub-arctic regions is the compromise of structural integrity of the pipe. Leakage of highly flammable natural gas from broken pipe is potentially dangerous and may cause significant damage to properties and even loss of lives.

There have been a range of improvements in pipeline construction and the advancement of manufacturing techniques has improved the structural integrity of steel pipe recently. However, leakage from chilled gas pipelines is still possible, particularly caused by the aging of the natural gas infrastructure. Current leak detection systems are based on sniffing or drawing of air samples from inspection location. Gopalsami and Raptis (2002) in Argonne National Laboratory present a state-of-the-art survey of using remote sensing techniques in the context of detecting and locating natural gas leaks. Argonne National Laboratory (2002) also proposed to develop a microwave radar method for remote and fast imaging of gas leaks. However, the leakage from buried chilled pipelines constructed in cold regions may present characteristics that are significantly different from those in other regions because of the frozen ground. The dissemination of released gas in frozen ground may also likely to exhibit far different characteristics than those normally encountered in other regions. In this study, laboratory experiment studies will provide a preliminary understanding of the process of gas dispersion in frozen ground. Computer modeling studies based on laboratory findings may also provide valuable information.

1.2 Laboratory Experiment Studies on Gas Permeability of Frozen Soil

Extensive efforts have been made to document those engineering and environmental problems encountered in the Arctic and Sub-arctic regions. However, relatively little research has been carried out to evaluate the dispersion process of released methane plume in the frozen ground around buried pipes. The characteristics of gas dispersion in permafrost under various ground conditions are not well understood. In order to understand the different process of gas dispersion in frozen ground, a preliminary laboratory experiment was designed and conducted to study the characteristics of gas permeability of frozen soil.

In the experiments, the ground temperature, the water/ice content and the ground stress are considered to have significant impact on the gas permeability of frozen soil. The effects of these parameters on gas permeability in frozen soil are, therefore, investigated.

Chapter 2

Literature Review

In this chapter, a literature review is presented. The review covers previously published information on the characteristics of gas dissemination in frozen ground, the properties of frozen soils and the characteristics of the thermal regime in frozen ground. The information from these previous studies is used as guidance for the designs of the laboratory experiments in this study. The literature search also covers the information on laboratory soil testing techniques and procedures, particularly the standards from different professional associations, which are the basis of the laboratory experiments developed in this study. Furthermore, the review includes literature search on the theory of permeability and the principles of fluid dynamics that serves as the foundation for the numerical simulations of gas dissemination in frozen ground.

2.1 Physical Properties of Frozen Ground

The development of energy resources and the need for highways, pipelines, and other civil construction in the cold regions have created a need for geotechnical information on seasonal and permanently frozen ground. Therefore, much research work has been conducted to study the physical properties of the frozen soil. Frozen soil is a four-component material consisting of soil particles, ice, water, and air (Andersland and Ladanyi, 1973). Recognition of the interaction of these components and their distribution in the system under various states of stress is basic to an understanding of the properties and engineering behavior of frozen ground (Anderson and Morgenstern, 1973).

2.1.1 Classification of Frozen Soil

Frozen soils may be described as hard frozen, plastic frozen or dry frozen, depending on their pore ice and unfrozen water contents and their compressibility under load (U.S.S.R. 1969). From the above definition, a classification system for frozen soil has a concise description. The system for describing and classifying frozen soil involves three parts. In Part I, the soil phase is identified independently of the frozen state using the Unified Soil Classification System. Part II involves adding characteristics resulting from the frozen state to the soil description. In Part III, ice strata found in the soil are described (Linell and Kaplar, 1966).

The Unified Soil Classification System is the most commonly accepted system for unfrozen soils with three major divisions: coarse-grained soils, fine-grained soils and highly organic soils. In the extension of frozen soils, frozen soil characteristics are added based on two groups: soils in which segregated ice is not visible to the unaided eye (designation N) and soils in which segregated ice is visible (designation V). Subgroups for group N includes poorly bonded (Nf) and well bonded (Nb). And subgroups for group V includes a thickness of up to 25mm covering individual ice inclusion (Vx), ice coatings on particles (Ve), random or irregularly oriented ice formations (Vr) and stratified oriented ice inclusions (Vs). When visible ice is greater than 25mm, subgroups include ice plus soil type or only ice when no soil inclusions are present.

2.1.2 Unfrozen Water and Ice in Frozen Ground

The different properties of frozen soil at a given temperature may vary from relatively brittle to plastic dependent on the unfrozen water and ice contents. The formation of ice in soil pores has a great effect on frozen soils. Lunardini (1981) pointed out ice formation involves cooling of a soil-water system and the pore water does not out ice formation involves cooling of a soil-water system and the pore water does not start to freeze until the temperature drops to Tsc that means the water is in a super-cool condition. Then the super-cooled water is in a metastable equilibrium state until an abrupt transformation of free water to ice is triggered by the nucleation center. Formation of ice releases latent heat, causing a rise in the temperature to Tf, the initial freezing temperature. All the free water and most of the bound water (unfrozen water film on the soil particles) are frozen at Te (about -70˚C) (Andersland, 1994). The cooling curve is shown in Figure 2.1:

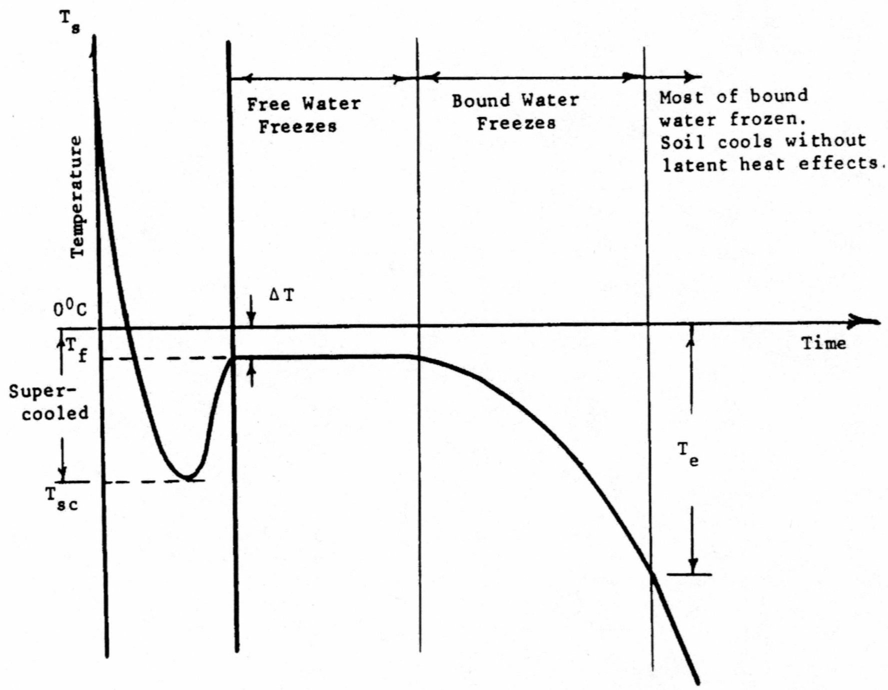


Figure 2.1 Cooling Curve for Soil Water and Ice (Lunardini, 1981)

Not all the water freezes when fine-grained soils are subjected to freezing temperatures. They may contain significant amounts of unfrozen water, particularly in the range of temperatures (-10˚C to 0˚C) that are of practical importance to the engineers. Tice, et al. (1976) has summarized experimental unfrozen water contents for several soils content of remolded frozen soil can be conveniently represented by a simple power curve of the from:

$$Wu = \alpha \times \theta^{\beta}$$

Where, Wu is unfrozen water content, α and β represent characteristics soil parameters and θ is the temperature expressed as a positive number in degree Celsius below freezing. Here, for Fairbanks silt α= 4.81 and β= —0.33.

2.1.3 Freeze-Thaw Effects in Frozen Ground

Repeated freezing and thawing of clayey soils will produce an increase in the effective void ratio. Konrad (1989) has reported that this leads to a reduction in the segregation potential, which is defined as the ratio of water-intake rate to the temperature gradient in the frozen soil near the frost front, after each freeze-thaw event and to an increase in vertical hydraulic conductivity of the thawed soil. Konrad (1989) also pointed out the changes in hydraulic conductivity occurred primarily during the first three freeze-thaw cycles.

2.2 Temperature Profile in Frozen Ground

Ground temperatures have a significant effect on frozen soil behavior and are determined by air or surface temperatures, heat flow from the interior of the earth, and soil thermal properties. In addition to dependence on variable surface factors, ground temperatures may also depend on construction activities (Andersland, 1994).

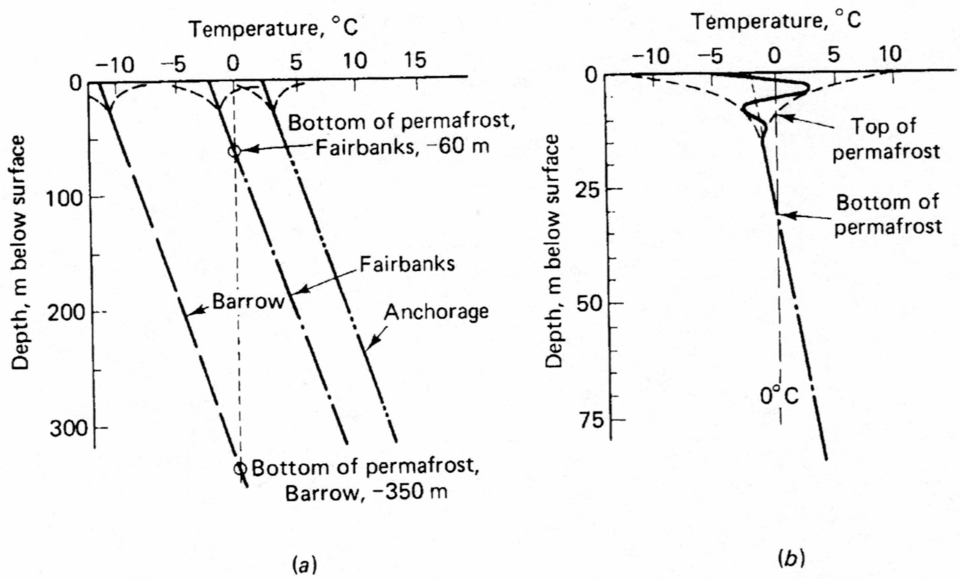
Rice (1996) pointed out that the surface temperature of the world is determined by a complex set of interactions between solar radiation, radiation to and from the sky, and the near surface conditions established by clouds, wind, rain, water and terrain. Brown (1963) reported that mean annual ground temperatures (of 1 cm depth) differ from mean

(1963) reported that mean annual ground temperatures (of 1 cm depth) differ from mean annual air temperatures. However, there is no constant difference between them. Then surface indices are estimated using an empirically determined surface n-factor that defined as the ratio of the ground surface freezing index (Isf) to the air freezing index (Iaf). The air freezing index is the number of negative (T<0°C) degree-day.

Rice (1996) explained that the heat flow from the interior to the surface of the earth results in a remarkably constant temperature gradient throughout the earth. In another word, the temperature gradient is about the same in the arctic as in the tropic regions. Apart from volcanic regions, the gradient is somewhere about 3 Celsius degree per 100 meters. Wherever the average soil surface temperature is a degree or so colder than freezing water, permafrost will be present in the soil and the colder the average surface temperature, the thicker the permafrost will be. Several local factors and seasonal temperature variations complicate the temperature in the first 10 to 20 meters of the surface soil throughout the year.

The annual ground-temperature variation decreases steadily from the ground surface to the depth of 6 to 15 m or more. Below this depth the temperature increases steadily under the influence of heat generated deep in the earth, doubtless in major part by nuclear decay. Johnston (1981) also thought below the depth, the ground temperature change only in response to the geothermal flux and the changes in climatic conditions extending over centuries.

The temperature profile, namely Whiplash Curve, in Alaska area is shown as follows (see Figure 2.2):



Near-ground-surface temperature relationships and the geothermal gradient: (*a*) average ground temperature depends on depth and average surface temperature; (*b*) variation of ground temperatures by seasons, the *whiplash curve.*

Figure 2.2 The Temperature Profile in Alaska Area (Andersland, 1978)

2.3 Laboratory Testing Standards and Procedures

Many professional associations of engineering in the USA, such as ASTM (American Society for Testing and Materials), ASCE (American Association for State Highway and Transportation Officials) and others, have published professional standards or specifications in their work and research areas. These publications play very important roles in engineering designs and constructions. The engineering designs and works have to follow the standards that have been accepted by most engineers in the professional area. The standards are updated by the professional associations periodically because of the progress in the respective professional areas.

2.3.1 ASTM Standards

ASTM (American Society for Testing and Materials) is a scientific and technical organization formed for "the development of standards on characteristics and performance of materials, products, systems, and services; and the promotion of related knowledge." ASTM publishes the standards to meet the approval requirements of appropriate safety and health practices. The designation: D421-85 "**Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants**" describes the preparation of dry soil samples and D2217-85 "**Standard Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants**" introduces the preparation of wet soil. The experiment requires the uniformity of the soil samples (such as uniform density). The standards D4253-83 "**Standard Test Methods for Maximum Index Density of Soils Using a Vibratory Table**" and D4254-83 "**Standard Test Methods for minimum Index Density of Soils and Calculation of Relative Density**" provide the methods of the measurement of density of soils and illustrate the apparatus that are different molds.

2.3.2 AASHTO Standards

AASHTO (American Association for State Highway and Transportation Officials) is also a professional association that publishes **Standard Specifications for Transportation Materials and Methods of Sampling and Testing**. The standard specifications include two parts. Part I contains specifications for materials, and Part II includes methods of testing and specifications for testing equipment. AASHTO has her own features although many of the specifications consistent with those of ASTM. That is because AASHTO serves for the Department of Transportation in common, while ASTM serves for the entire engineering society. Designation T87-86 "**Dry Preparation of Disturbed Soil and Soil Aggregate Samples for Test**" describes the dry preparation of soil and soil-aggregate samples and T146-96 "**Wet Preparation of Disturbed Soil and Soil Aggregate Samples for Test**" covers the wet preparation of soil samples. T99-97 "**Moisture-Density Relations of Soils Using a 2.5kg (5.5-lb) Rammer and a 305-mm (12-in) Drop**" is intended to determine the relationship between the moisture content and density of soils compacted in a mold of a given size with a 2.5-kg (5.5-lb) rammer dropped from a height of 305 mm (12-in). T99-97 also introduces cylindrical mold and base plate. T180-97 "**Moisture-Density Relations of Soils Using a 4.45kg (10-lb) Rammer and a 457-mm (18-in) Drop**" is the same intention as T99-97, but using a different size mold and a heavier rammer dropped from a higher elevation.

2.3.3 Other Laboratory Manual

Das (1997) also introduced the common soil laboratory procedures and equipments that are essential in understanding the properties of soils and their behavior under stress and strain in the book of "**Soil Mechanics Laboratory Manual**". "**Standard Proctor Compaction Test**" and "**Modified Proctor Compaction Test**" describe the laboratory compaction test procedure to determine the maximum dry unit weight of compacted soils that can be used for specification of field compaction. The major equipments required include a compaction mold, No. 4 U.S sieve, a standard proctor hammer, a scale, a large flat pan, and a steel straight edge.

2.4 The Theory of Permeability and the Principle of Fluid Dynamics

The gas flow pattern in frozen ground – flow of compressive fluid – is governed by the theory of permeability and the principle of fluid dynamics. A review of pertinent theories will assist the development of mathematical/numerical models that simulate the gas flow pattern in frozen ground for the study of gas flow characteristics.

2.4.1 Theory of Permeability

2.4.1.1 Darcy's Law

Permeability is the capacity of a material to transmit the fluid (i.e. gas or water). It depends on the properties of a material and the fluid to be transmitted. Henry Darcy (1803 - 1858) was the first researcher to develop the law for laminar flow in porous media, known as Darcy's Law now. Beginning in 1940, Hubbert (1969) wrote some influential essays on Darcy's Law. He found that Darcy's Law could be as a proportionality between flow rate and pressure gradient alone, which is widely used in most textbooks. Today Darcy's Law is a foundation stone for several fields of study including ground-water hydrology, soil physics, and petroleum engineering.

Darcy's Law governing the laminar flow of water in saturated soils can be written as (Smoltczyk, 2002):

$$V = -\frac{q}{A} = -k \times i = -k\frac{\Delta h}{\Delta l} \qquad (2.1)$$

Where, q is the quantity of water flowing in unit time (flow rate). A is the area through which the flow occurs, v is the apparent flow velocity, i is the hydraulic gradient, Δh is the difference in pressure head, Δl is the flow path, and k is coefficient of water permeability.

In unsaturated soils and rocks, the gas can also flow through them continuously. The flow of gas in the continuous air phase is controlled by the pressure gradient. Darcy's Law can be used to describe the flow. The equation to describe the steady state gas flow is (Smoltczyk, 2002):

$$V = -\frac{k}{\mu}\frac{dP}{dl} \qquad (2.2)$$

Where k is the coefficient of gas permeability, V is the flow rate, μ is the viscosity of gas, P is the pressure and l is the length, dP/dl is the pore-air pressure gradient in one direction.

As early as 1941 Klinkenberg reported variations in permeability determined by using gases as the flowing fluid compared to those obtained when using non-reactive liquids. These variations were considered to be due to slippage, a phenomenon well known with respect to gas flow in capillary tubes. The phenomenon of gas slippage occurs when diameter of the capillary openings approach the mean free path of the gas. Therefore, permeability of gas depends on not only the media but also factors that influence the mean free path. Klinkenberg noted that a plot of k versus 1/Pmean, Pmean being the average pressure between the inlet and outlet, yields a straight line, with the slope dependent on the gas's identity. Lower-weight molecular gases display a greater slope - a result of the greater mean free path. All gases, regardless of identity, have the same y-intercept on such a graph when the data is extrapolated to 1/Pmean = 0. Figure 2.3 shows the variation in gas permeability with mean pressure and type of gas. This limit corresponds to the k-value for liquid flowing through rock, which is independent of the liquid identity. A gas in such a situation is compressed into a liquid-like state. This k is the permeability of a liquid that completely fills the pores of a medium.

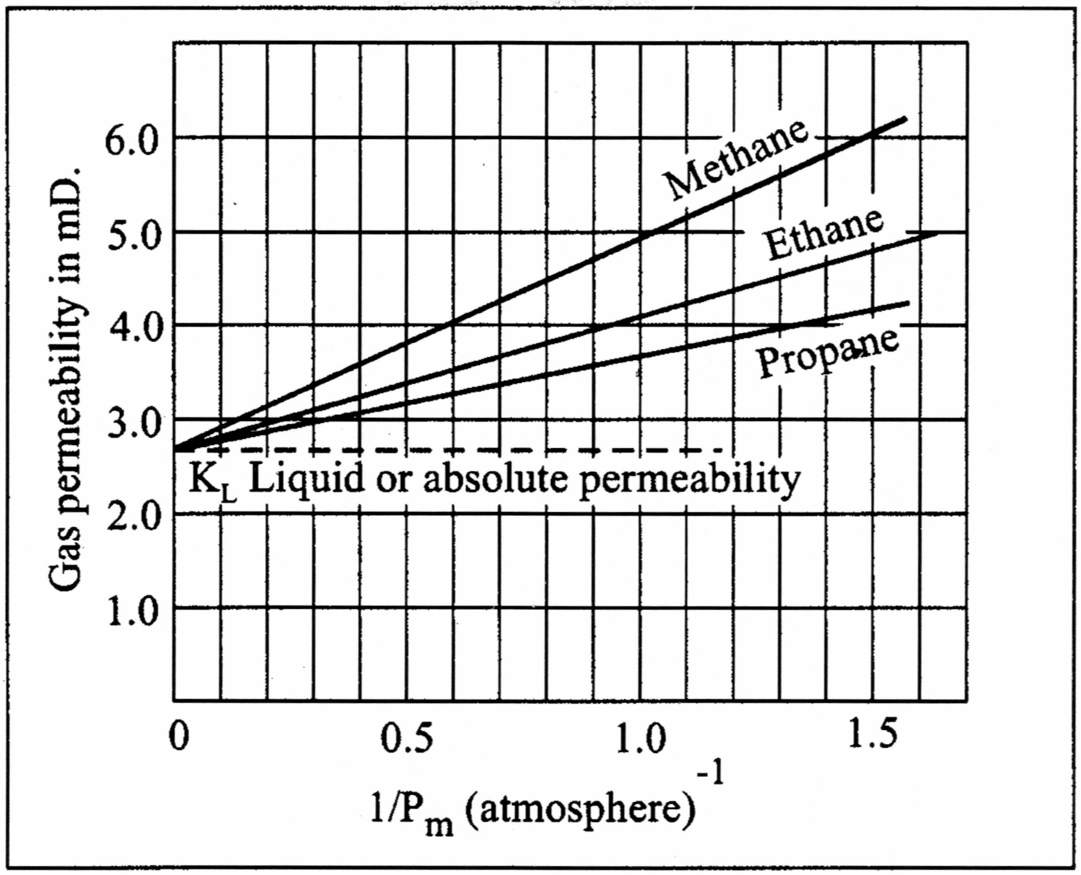


Figure 2.3 Variation in Gas Permeability with Mean Pressure and Type of Gas (Torsæter and Abtahi, 2000)

The following equation, relates the apparent gas permeability, kg, of a gas flowing at an average pore pressure Pmean, to the liquid permeability of the porous medium, k_L (Klinkenberg, 1941):

$$kg= k_L *(1+b/Pmean) \quad (2.3)$$

Where, the constant b is a constant dependent on the capillary radius, rb, and the mean free path of the gas, λ at the pressure Pmean and is given by (Klinkenberg, 1941):

$$b= 4c\ \lambda Pmean/rb \quad (2.4)$$

In equation (2.4), c is a constant approximately equal to one.

From the equation (2.4), the contribution resulting from the slip is inversely proportional to the capillary radius. The slip effect become more significant because of the small pore size at mean pore pressures usually employed in the laboratory measurements of permeability.

Darcy' Law is a phenomenological law rather than a fundamental law. Freeze (1979) pointed out: "Darcy's law is an empirical law. It rests only on experimental evidence", although Shrader-Frechette (1989) repeatedly referred to it as either a "theoretical" law in a recent discussion of Darcy's law. The present concerns are the recognition of both lower and upper bounds for the dependable use of the law's stated relationships. The upper limit is of more practical significance for the engineers. Experimental studies show the law is not valid when the flow regime is not laminar nor dominated by viscous forces. The Reynold's number, a dimensionless ratio of inertial forces to viscous forces, affects on the determination of laminar flow. At low Reynold's number, viscous forces dominate, and Darcy' law is valid.

2.4.1.2 The Gas Permeability of Rock

In petroleum engineering, the design of stimulation treatment to treat commercial rates of production and reliable assessment of potential reserves in low-permeability rocks demands accurate knowledge of their permeability and porosity.

Thomas and Ward (1972) reported that the permeability of cores from the Pictured Cliffs and Fort Union formations were affected significantly by confining pressure. Their studies also showed that presence of a simulated connate water saturation (about 50%) reduced gas permeability to only 10% to 20% of the specific gas permeability. Jones and Owens (1980) also found that confining pressure reduces permeability of tight gas sands from two to more than 10 times, depending on permeability and rock type. Generally, the lower the core permeability the more it is affected by confining pressure. They also concluded that water (including brine) severely reduced permeability with the effect more pronounced in lower permeability rocks.

Gas slippage effects (Klinkenberg, 1941) may play a significant role in gas flow. It has been investigated extensively in single-phase flow. Jones and Owens (1980) reported that gas slippage effects were found to be substantial in tight gas sands. Sampath and Keighin (1982) discussed the factors affecting gas slippage in tight sandstones. They found that the extrapolated gas permeability of tight sandstones is affected significantly by confining pressure. Gas-liquid related two-phase flow is still not clearly understood. Li (2001) reported that gas slippage affects gas (both nitrogen and steam) relative permeability significantly. Li also discussed the effect of the temperature and slip factors increase with temperature.

2.4.1.3 The Permeability of Frozen Soil

The permeability of frozen soil is most likely affected by several factors including soil particle size, moisture content (frozen and unfrozen), microstructure of the soil, ground temperature, and confining pressure. Many researchers, including Konrad (1989), demonstrated the effect of freeze-thaw cycles on the frozen soil. They have observed that freezing and thawing affects the permeability of frozen soil. Benoit and Bornstein (1970) reported that freezing and thawing tends to break down the large soil aggregates of tilled soils and decrease permeability. Smith and Porkhaev (1972) observed that freezing and thawing increase the permeability of fine-grained soils. Chamberlain and Gow (1978) concluded that freezing and thawing caused a reduction in void ratio and an increase in vertical permeability. Konrad (1989) has reported that repeated freezing and thawing affect the structure of clayey silts over a wide range of consolidation ratios. In a word, they all found that freezing-and-thawing causes significant structural changes, and consequently affects the gas permeability of frozen soil.

2.4.2 The Principle of Fluid Dynamics

Zucrow and Hoffman (1976) described the governing laws in gas dynamics. They pointed out that the analysis of a physical situation involving the flow of a fluid is based on determining, for specific situation at hand, the forms. The forms were taken by the equations expressing following physical laws:

1. The law of conservation of mass (the continuity equation)

2. Newton's second law of motion (the momentum equation)

3. The first law of thermodynamics, which expresses the principle of the conservation of energy (the energy equation)

4. The second law of thermodynamics (the entropy equation)

5. Thermodynamics properties of the fluid, from the tables of its properties, empirical equations, or an idealized model, such as the equation PV=RT for a thermally perfect gas.

Wendt (1992) introduced the equations of flow that are mathematical expressions describing the motion of compressible fluids in the book of **Computational Fluid Dynamics An introduction**:

Equations for Viscous Flow:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla\left(\rho \vec{V}\right) = 0$$

Momentum equation:

x component: $$\frac{\partial(\rho u)}{\partial t} + \nabla\left(\rho u \vec{V}\right) = -\frac{\partial P}{\partial x} + \frac{\partial(\tau_{xx})}{\partial x} + \frac{\partial(\tau_{yx})}{\partial y} + \frac{\partial(\tau_{zx})}{\partial z} + \rho f_x$$

y component: $$\frac{\partial(\rho v)}{\partial t} + \nabla\left(\rho v \vec{V}\right) = -\frac{\partial P}{\partial y} + \frac{\partial(\tau_{xy})}{\partial x} + \frac{\partial(\tau_{yy})}{\partial y} + \frac{\partial(\tau_{zy})}{\partial z} + \rho f_y$$

z component: $$\frac{\partial(\rho w)}{\partial t} + \nabla\left(\rho w \vec{V}\right) = -\frac{\partial P}{\partial z} + \frac{\partial(\tau_{xz})}{\partial x} + \frac{\partial(\tau_{yz})}{\partial y} + \frac{\partial(\tau_{zz})}{\partial z} + \rho f_z$$

Energy equation:

$$\frac{\partial}{\partial t}\left(\rho\left(e + \frac{V^2}{2}\right)\right) + \nabla\left(\rho\left(e + \frac{V^2}{2}\right)\vec{V}\right) = \rho\dot{q} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial y}\right)$$
$$-\frac{\partial}{\partial x}(uP) - \frac{\partial}{\partial y}(vP) - \frac{\partial}{\partial z}(wP) + \frac{\partial}{\partial x}(u\tau_{xx}) + \frac{\partial}{\partial y}(u\tau_{yx}) + \frac{\partial}{\partial z}(u\tau_{zx}) + \frac{\partial}{\partial x}(v\tau_{xy})$$
$$+\frac{\partial}{\partial y}(v\tau_{yy}) + \frac{\partial}{\partial z}(v\tau_{zy}) + \frac{\partial}{\partial x}(w\tau_{xz}) + \frac{\partial}{\partial y}(w\tau_{yz}) + \frac{\partial}{\partial z}(w\tau_{zz}) + \rho\vec{f} * \vec{V}$$

Where, ρ-density of the gas; P-pressure; A-cross sectional area; u-velocity; q-discharge; k-permeability; μ-absolute viscosity; t-time; u, v, w-vector velocity in the Cartesian space; x, y, z-distance. The variables such as velocity, pressure, and density are determined at fixed points of space at each instant time t, so that: V= V (x,y,z,t), P= P (x,y,z,t), ρ= ρ (x,y,z,t), u= u (x,y,z,t), v= v (x,y,z,t), w= w (x,y,z,t), $\vec{V} = u\vec{i} + v\vec{j} + w\vec{k}$.

The equations controlling the gas dynamics are very complicated. Kentfield (1993) deduced a series of simpler equations for one-dimensional, non-steady, internal, compressible flow. The assumptions are:

(1) The walls of the flow duct are very smooth and the friction of walls is not taken into account by means of a friction force.

(2) There is no heat interaction with the surroundings for the flow channel or only negligible amounts of heat are transferred.

(3) Thermal influences of exothermic or endothermic reactions are not taken into account.

(4) Flow-channel cross-sectional area can vary as a function of x (only) within limitations consistent with a one-dimensional flow model.

Equations for one-dimensional, non-steady, internal, compressible flow:

Continuity equation:

$$\frac{d\rho}{dt}+u\frac{d\rho}{dx}+\rho\frac{du}{dx}+\frac{\rho u}{A}\frac{dA}{dx}=0$$

Momentum equation:

$$\rho\frac{du}{dt}+\rho u\frac{du}{dx}+\frac{dP}{dx}+\frac{\rho u^2}{A}\frac{dA}{dx}=0$$

Energy equation:

$$\frac{dP}{dt}+u\frac{dP}{dx}-a^2\left(\frac{d\rho}{dt}+u\frac{d\rho}{dx}\right)+\frac{\rho u}{A}\frac{dA}{dx}=0$$

Where, a-speed of sound, other parameters are mentioned above.

The principle of fluid dynamics is a theoretical law, while Darcy's law is an empirical law. The equations describe a very strict law are hardly to solve the problem analytically. Numerical solution is necessary for many engineers to resolve practical problems.

Chapter 3

Laboratory Experiments

3.1 Introduction

In this study, laboratory experiments were conducted to gain a better understanding of the characteristics of gas dispersion in frozen ground. Well-designed laboratory experiments are necessary for an accurate and in-depth study of gas flow characteristics in frozen ground. The design of experiments includes two parts: (1) the design and development of the experimental equipments, and (2) the design of the preparation procedure of frozen soil samples to be tested. Then follow the sample testing and equipment operating procedure to measure gas permeability.

For the laboratory experiments in this study, the accurate measurement of the gas flow through the soil samples is the key for the estimation of the gas permeability. If the soil samples cannot be sealed tightly, the results of experiments will be inaccurate. The sealing requirement for the testing apparatus is of the same importance. The gas leakage must be maintained at a minimal level in order to obtain a reasonable accurate reading of the gas permeability in frozen soil. In order to conduct the experiments safely, nitrogen is used instead of the methane gas since methane is flammable and potentially dangerous.

In the laboratory experiments, another important step is the preparation of soil samples. The key of laboratory of soil samples preparation is to ensure the uniformity of remolded soil samples equalities because the properties of in-situ soil are dispersed and each constituent of soil may not be well distributed. The experiment is designed to test a large number of soil samples with various conditions. The remodeled soil samples will allow the experiments to be conducted under different temperatures and moisture contents. ASTM and AASHTO published the standards and developed the methods based on the requirements of appropriate safety and health practices. The method to remold the soil samples is developed with reference to these standards.

3.2 The Development of the Test Equipment

For the equipment design, the key requirement is to prevent or minimize gas leakage from the system in order to ensure accurate measurement of the test results. In addition, all the apparatus and the gas used in the experiments should be safe to operate in the laboratory. Furthermore, the test system should be easy and efficient to operate.

The testing system includes the following components: (1) Gas permeameter, (2) Soil sample holder, (3) Cooling coil system and (4) Nitrogen bottle and tubings. The schematic drawing of the equipment system is shown in Figure 3.2.1, and the testing equipment is shown in Figure 3.2.3.

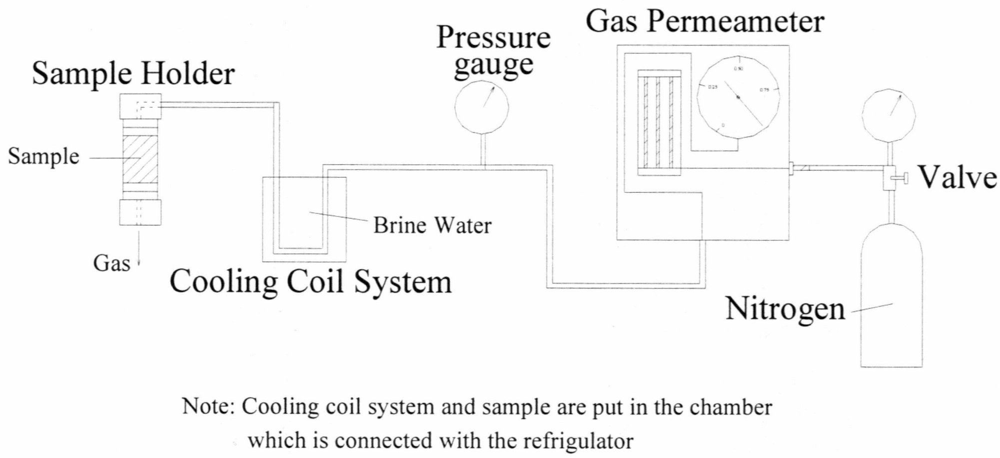


Figure 3.2.1 Schematic Diagram of Testing System

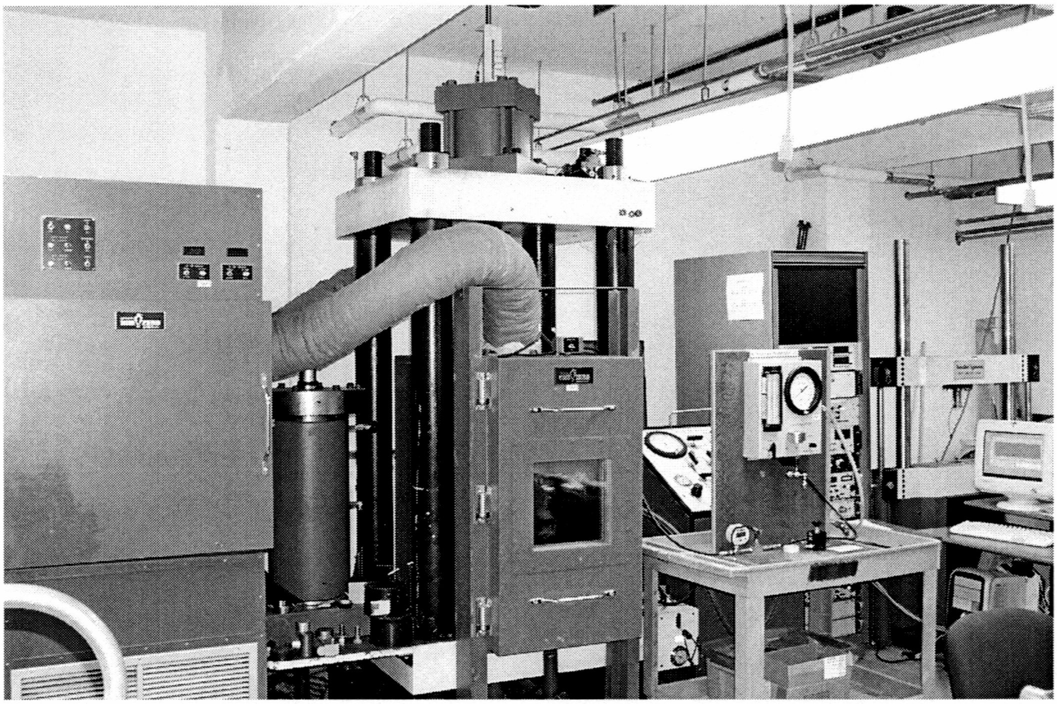


Figure 3.2.2 Laboratory Testing Equipment

3.2.1 The Gas Permeameter

The Ruska Gas Permeameter (Figure 3.2.3) is an instrument for measuring the permeability of consolidated core sections by forcing a gas of known viscosity through a core sample of known cross section and length. Pressure, temperature and flow rate of the gas through the sample are measured. The instrument consists of (1) a sample coreholder designed for the sealing of soil sample, (2) triple range flowmeter with selector valve, (3) calibrated Bourdon tube pressure gage, (4) pressure regulator, with (5) gas inlet connection, which are permanently interconnected and counted on a panel with frame. The sample coreholder attached to the Ruska Gas Permeameter was not used in this study. Instead, a specially designed coreholder was used to meet the requirement of the experiments.

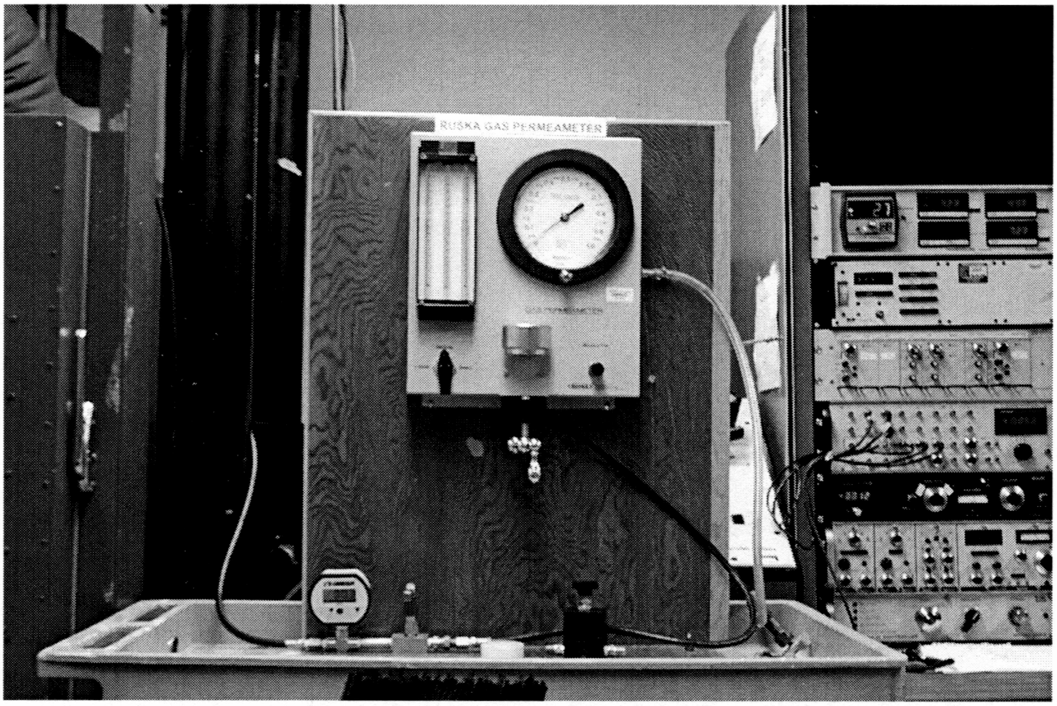


Figure 3.2.3 Gas Permeameter

3.2.2 Soil Sample Coreholder

The soil sample coreholder is designed to seal soil sample in such a manner that the gas entering can escape to the atmosphere only after passing lengthwise through the sample. The desired gas pressure (upstream pressure in atmospheres) is adjusted with the regulating valve and is read on the pressure gage on the gas permeameter. The gas flow is determined by the height of the center of the float in one of the flowmeter tube. At the same time, the design of the sample holder is aimed to facilitate the application of different axial load on the sample, since the load applied is considered an important factor affecting gas dissemination in the frozen ground.

The coreholder includes two parts: the vessel and two holders (Figures 3.2.4 and 3.2.5).

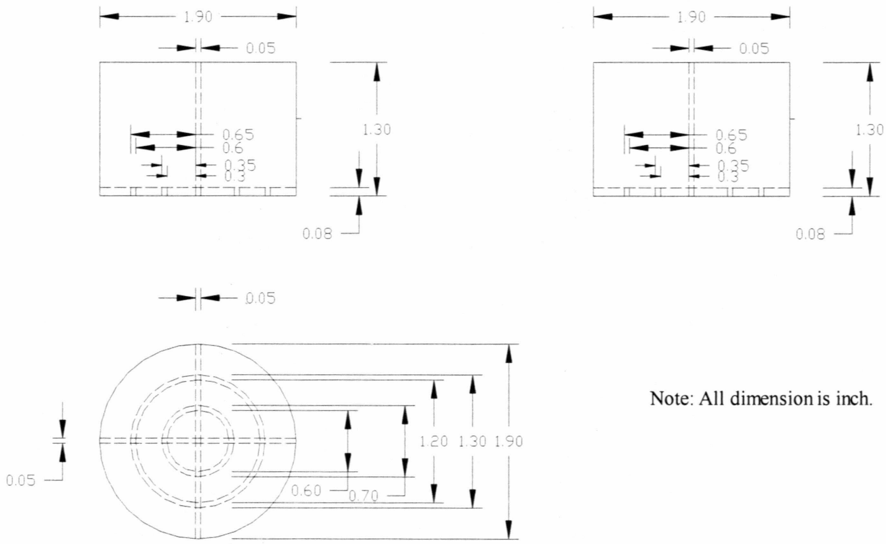


Figure 3.2.4 Coreholder Design

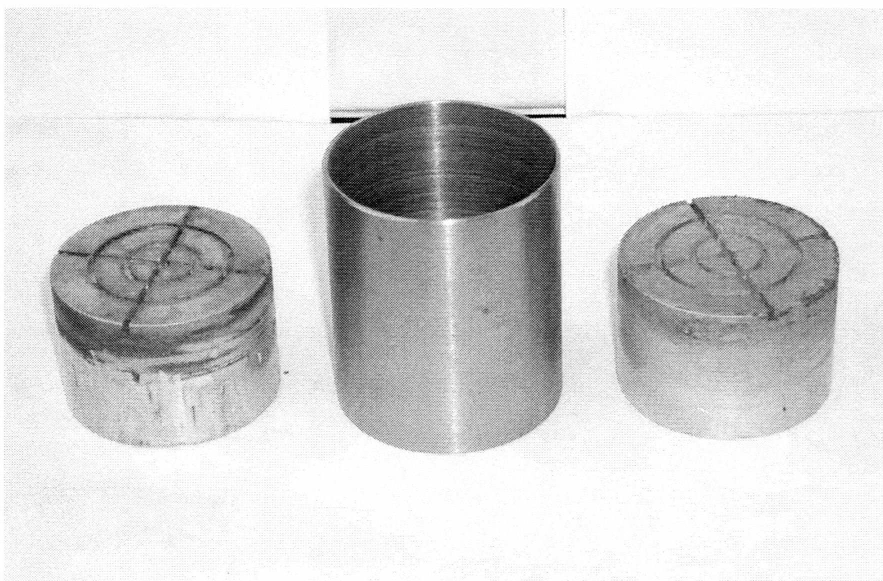


Figure 3.2.5 Fabricated Coreholder

In order to connect and seal the soil samples, two metal end connectors and a rubber holder were used as shown in Figure 3.2.6.

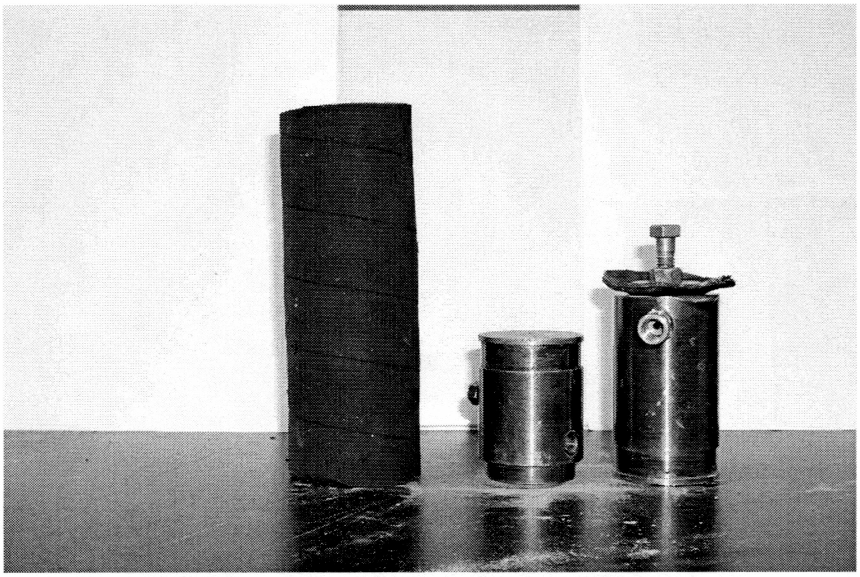


Figure 3.2.6 Metal End Connectors and Rubber Holder

3.2.3 Cooling Coil System

Cooling coil system is designed to cool down the nitrogen gas that flows through the sample to the same temperature as the sample. During the experiment, the soil sample is frozen and the temperature of soil sample is below freezing point. If the nitrogen gas is not cooled down to the same temperature, the warm gas will thaw the soils and change the texture of the soils producing inaccurate results. The design of the cooling coil system is simple but very helpful for accurate temperature measurement during the experiments. As shown in Figure 3.2.7, the cooling coil system includes (1) the copper coil, (2) the aluminum can and (3) the brine water that can keep the solution in liquid state below 0°F (-18°C).

Figure 3.2.7 Cooling Coil

In the experiment, the temperature of the soil sample could not be measured directly because the whole sample was sealed in the coreholder and the use of the outer rubber holder. Initially the air temperature of chamber was measured to obtain the temperature of the sample with the assumption that the temperature between the sample and air will be the same after a certain period. However, this measurement method was inaccurate. Due to a significant difference between the specific heat of the soil sample and that of the air, temperatures in the two media may differ greatly even after a long period of time. The use of the cooling coil system improves the situation. The cooling coil system was put in the cold chamber with the soil sample. Since the specific heat of the soil is close to that of the brine water, it is reasonable to assume that the soil sample has the same temperature as the brine water after half an hour. The brine water temperature was then measured to obtain the temperature of the sample. Although there may still be error in the measurement, it is considered acceptable for the experiments.

3.2.4 Nitrogen Bottle and Tubings

The experiment was designed to use nitrogen instead of the methane gas or air. Methane gas is flammable and potentially dangerous. Natural air contains moisture. When air passes the cooling coil system and the soil sample, water may freeze and change to ice, affecting the test results. Therefore, the stable, pure and dry nitrogen was selected in the experiment. In the experiment system, all the tubes were designed to connect tightly and not allow gas to leak from it. The entire system was examined before each experiment.

3.3 The Preparation of Soil Samples

Soil samples were taken from a pipeline experiment site near Fairbanks, Alaska. It is silt to slightly sandy silt, mostly between 0.001 and 0.1mm in grain size. The organic contents of the soils range from 1.8% to 9.9%, with an average of 4.8% and a standard deviation of 1.7%. The properties of in-situ soil are dispersed, for example organic substances are not well distributed. In order to keep soil samples uniform, a series of methods recommended from ASTM and AASHTO were adopted to remold soils.

1. Firstly, the organic substances were removed out of the soils and dry soil was prepared (dry soil preparation).

2. Secondly, water was added to the dry soils to make the soils having the required water content (wet soil preparation).

3. Thirdly, the wet soil was compacted to keep the soil with uniform density (standard proctor compaction test).

4. Lastly, the compacted soil was placed inside the sample coreholder and sealed.

After the four steps, the soil sample was ready to be tested with the developed equipment system. With this procedure of soil sample preparation, the texture of the soil sample is different from the in-situ soils. However, the degree of fineness and uniformity of soil samples are better than the in-situ soils. The test results of the remolded soil samples should represent the average properties of the soil material.

3.3.1 Introduction to the Apparatus

3.3.1.1 Mold

The mold is a solid-wall, metal cylinder manufactured with dimensions and capacities shown in the picture below (Figure 3.3.1). The mold has a detachable collar assembly approximately 60 mm (2.375 in) in height, to permit preparation of compacted specimens of soil-water mixtures of desired height and volume. The mold and collar can be fastened firmly to a detachable base plate made of the same material.

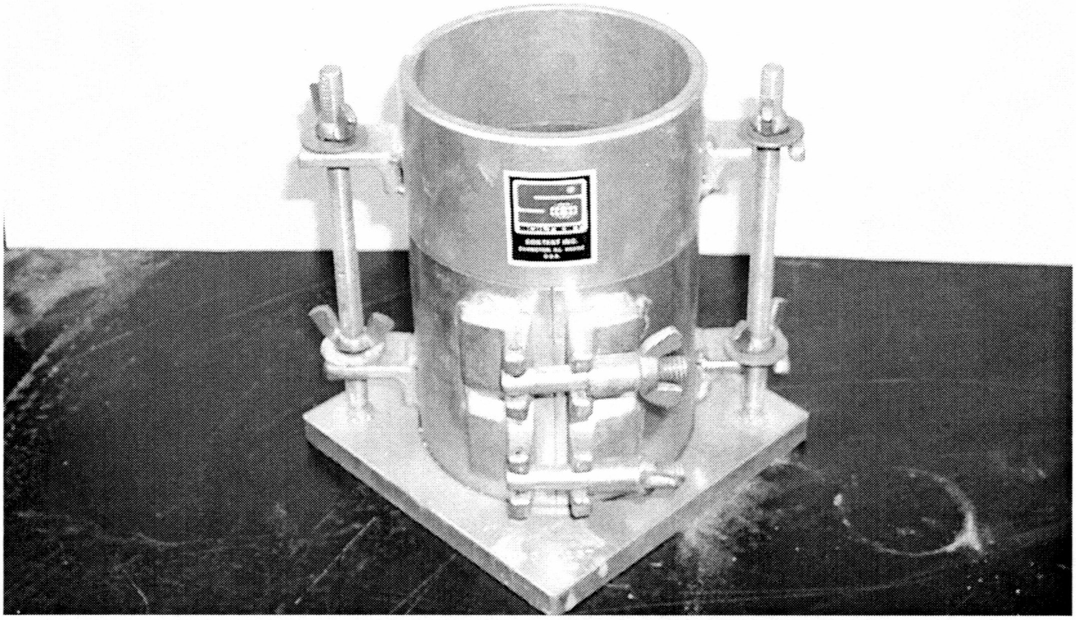


Figure 3.3.1 The Mold

3.3.1.2 Rammer or Standard Proctor Hammer

Metal rammer with a mass of 5.5 lb, has a flat circular face of 2.000-in diameter with a manufacturing tolerance of 0.01 in (Figure 3.3.2). The in-service diameter of flat circular face is less than 1.985 in. The rammer is equipped with a suitable guide-sleeve to control the height of drop to a free fall of 12-in above the elevation of the soil.

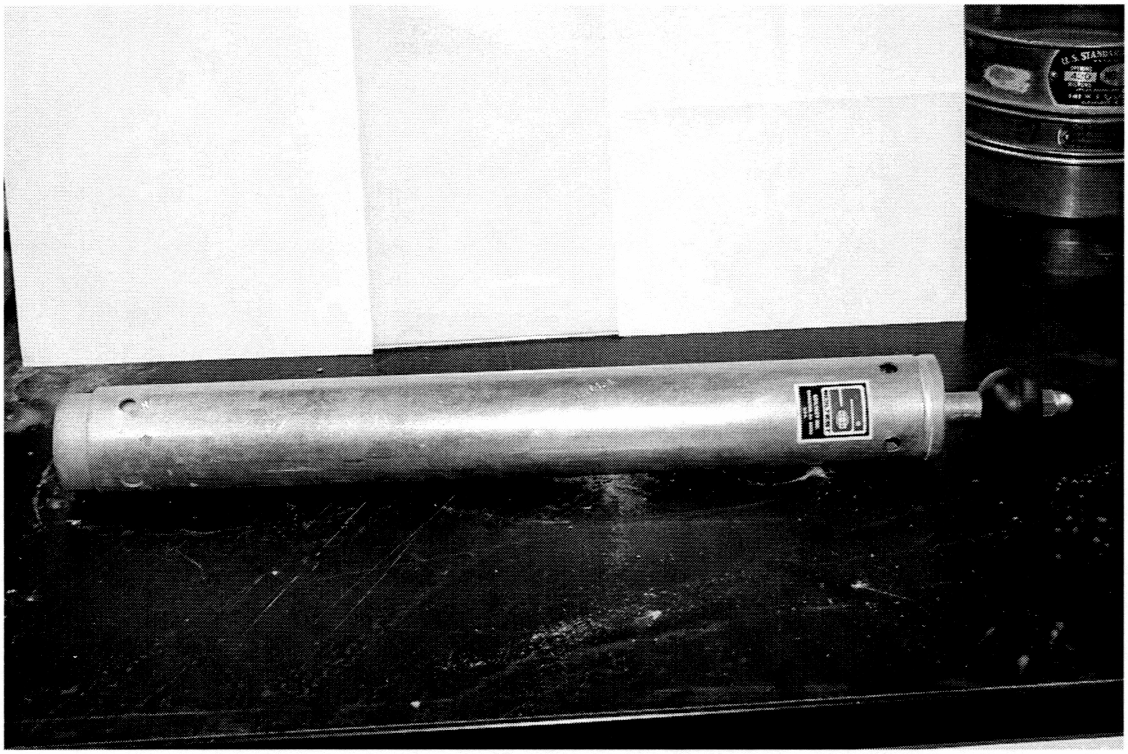


Figure 3.3.2 The Rammer

3.3.1.3 Drying Oven

A thermostatically controlled drying oven is capable of maintaining a temperature for drying moisture soils. The soils were dried in the oven. The temperature of oven was set to not exceeding 60°C (140 °F).

3.3.1.4 Sieves

No. 4, No10 and No.40 US sieves were utilized to sort the particles of soil (Figure 3.3.3).

3.3.1.5 The Flat Pan

The metal flat pan was used to retain the soil and mix soil sample.

Figure 3.3.3 Sieves and Flat Pan

3.3.1.6 Coreholder

The coreholder was introduced in section 3.2.2 previously.

3.3.1.7 Miscellaneous Tools

Different tools such as moisture cans, multi-purpose thread sealant, spoon, or a suitable mechanical device for scooping soil were also used in the experiments.

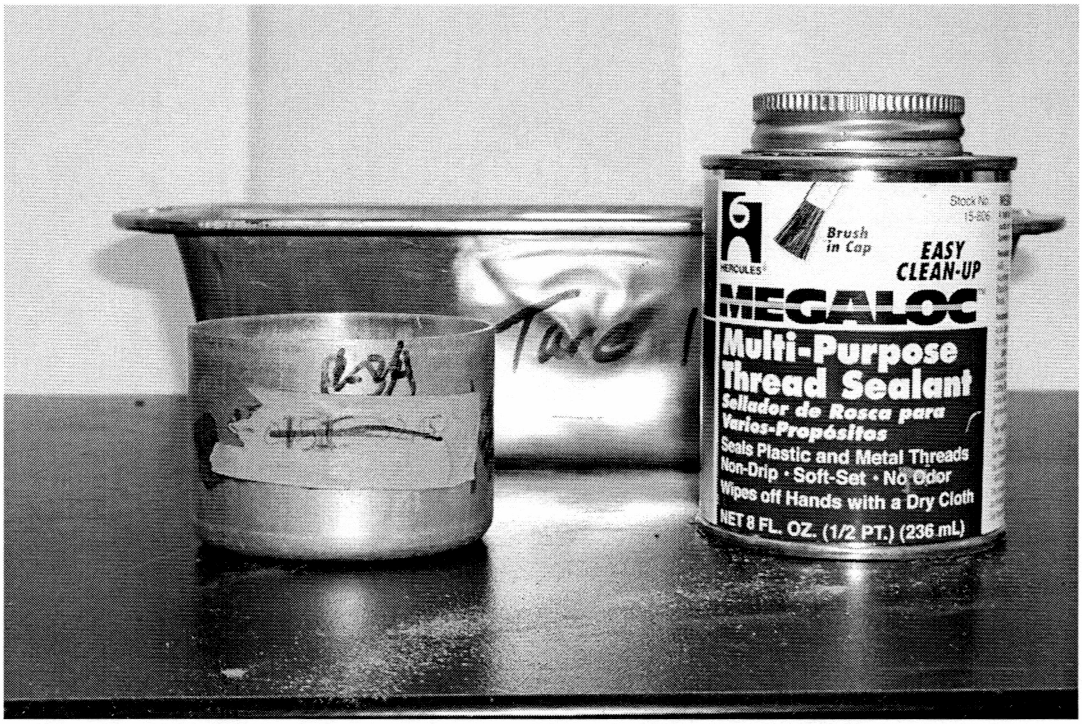


Figure 3.3.4 Miscellaneous Tools

3.3.2 The Procedure for Soil Sample Preparation

The procedure developed is based on ASTM, AASHTO and/or other laboratory standards.

3.3.2.1 Dry Soil Preparation

ASTM Designation D421-85 "Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants", Designation D2217-85 "Standard Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants" and AASHTO Designation: T87-86 "Dry Preparation of Disturbed Soil and Soil Aggregate Samples for Test" were referenced in the development of the preparation procedure of dry soils. The methods mentioned above describe the preparation of dry and wet soil and soil-aggregate samples for mechanical analysis, physical tests, moisture-density relations test, and other test.

The procedure of preparation of dry soils is as follows:

The original soils as received from the experimental pipeline site were exposed to the air at the room temperature until dried thoroughly or in a drying oven at a temperature not exceeding 140˚F (60˚C). Break-up of the aggregations was done in the mortar with a rubber-covered pestle or other suitable device.

Selection of a portion of the dried sample for tests was followed by separating the test sample by sieving with a No.10 (2.00-mm) sieve and grinding the soil fraction retained on the No.10 sieve in a mortar with a rubber-covered pestle until the aggregations of soil particles were broken up into separate grains. Then the ground soil was separated into two fractions by sieving with a No.10 sieve. At last, the portion of the material passing No.10 sieve was separated into two parts by means of a No.40 (425-µm) sieve. The fraction retained on the No.40 sieve (ASTM Standard) was discard and only the fraction passing No.40 sieve was used as the dry soil sample.

For drying the soils received from the field, there are two methods (I: exposure to the air and II: use of the drying oven) in ASTM and AASHTO Standard. However, there are different requirements in two standards. In ASTM standard, only method I is permitted in the dry preparation. For wet preparation, both methods are permitted. In AASHTO standard, the two methods are permitted in both dry and wet preparation. In this experiment, both methods were used.

3.3.2.2 Wet Soil Preparation

ASTM Designation: D2217-85 "Standard Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants" and AASHTO Designation: T 146-96 " Wet Preparation of Disturbed Soil Samples for Test" were followed in the development of the procedure for preparation of wet soils.

The procedure for preparation of wet soils is as follows:

1. Took the dry soil and put them into the flat pan.

2. Added water in sufficient amount into the dry soil to increase the moisture content to the required levels such as 10% or 20%. The soil was well mixed with water allowing the remolded soil to have evenly distributed moisture.

3. Sieved the damp soil through No. 10 sieve. The soils were separated by No.10 sieve and the fraction remaining in the sieve was forced to pass through the sieve. Any material remaining in the sieve was discarded at the end of the process. The fraction passing through the No. 10 sieve was the wet soil that had the required moisture content as designed.

During the above process, a slightly more water than required would be added into the soils due to some loss of water in the sample preparation process. The final moisture content in the soil was determined after completion of the experiment rather than the designed moisture content in the beginning. The actual moisture content may deviate slightly from the initial design. The experimental experience indicated that the final moisture content was about 3-5% lower than the initial water-soil mixture. In other word, if the soil samples required 15% water content, the water added into dry soils should allow an increased moisture content around 18% or so.

3.3.2.3. Standard Proctor Compaction

The compaction process is according to AASHTO Designation: T 99-97 " Moisture-Density Relationships of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in) Drop" and with reference from the book of "Soil Mechanics Laboratory Manual", edited by Braja M. Das, on "Standard Proctor Compaction Test". The method is developed to get a compaction soil samples that have uniform density.

The procedure of compaction is as follows:

1. Prior to compaction, placed the loose soil into the mold and spread into a layer of uniform thickness.

2. Lightly tamped the soil prior to compaction until it was not in a loose or fluffy state, using the manual compaction rammer.

3. Following compaction of the soils, any soil adjacent to the mold walls that had not been compacted or extended above the compacted surface should be trimmed using a knife or a straight edge, and be evenly distributed on the top of the layer.

Compacted each soil sample by 25 uniformly distributed blows from the rammer dropping free from a height of 12 in. During compaction, the mold was rested firmly on a rigid and stable foundation.

4. Following compaction, removed the extension collar, and removed the soil from the mold.

The soil samples were then ready to be installed into the coreholder.

In this experiment, the aim of compaction is to try to keep all the soil samples with uniform density. However, the soil material is fragile due to the soil characteristics and the limitation of the tools. In the experiment, when the soil was removed from the mold, it was in a broken form. That is different from the requirement of AASHTO Standard. The standard was originally from the laboratory compaction test procedure that was developed by Proctor (1933). The standard was developed to determine the maximum dry unit weight and optimum moisture content of soils after compaction and was used for specification of field compaction. This specification is necessary due to frequent needs of compacting soil to improve its strength for construction of highways, airports, and other structures. Although the requirement of the standard could not be met exactly in this experiment, the compaction process still improved the density uniformity of the soil samples.

3.3.2.4 Assembly of Soil Test Samples

After the above three steps, the soils were ready to be installed into the coreholder. As introduced in the section 3.3.2, the coreholder included three parts: the vessel and two end holders. Firstly, the multi-purpose thread sealant was coated around the inside wall of the vessel. Secondly, one end holder was inserted into the vessel at the bottom in order to hold the soil and the compacted soil was pushed into the vessel. Then the soil was compacted tightly using a small hammer in order to fully fill the one-inch section of the vessel. Thirdly, the second holder was placed on the top and the coreholder was compacted carefully again to make sure the soil sample was sealed tightly. The soil sample was then ready to be tested (Figure 3.3.5). Figure 3.3.6 shows the soil sample after testing and the sample was still frozen.

The use of the multi-purpose thread sealant was an improvement after several tests. In the beginning, the sealant was not used. It was found that the soil sample was not sealed well in the coreholder and the sample could slide out of the coreholder easily. Since the sealing requirement of the testing system is of most importance, the sealant was then added. The improvement with the sealant seemed to be significant.

Figure 3.3.5 Prepared Soil Sample Ready for Testing

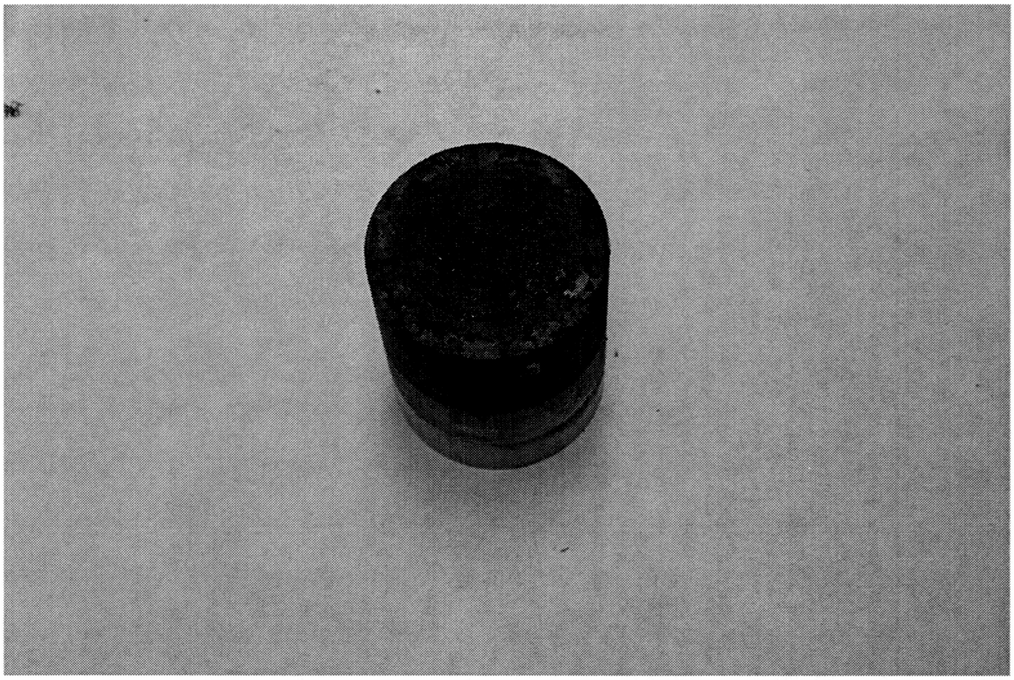


Figure 3.3.6 A Soil Sample after Testing (The sample was still frozen.)

3.4 The Operational Procedure of the Experiment

The prepared core soil sample was inserted in a rubber holder and sealed, and all parts of the testing system were connected. The system was checked to make sure there was no leakage and freeze to the required temperature. The valve of the nitrogen bottle was then open. The selector valve on the flowmeter was then turned to “large”, and the pressure-regulating valve was slowly opened until the pressure gage read 0.25 atmosphere. The preferred range on the flowmeter tubes was between 20 and 140 divisions. If the float in the large tube rose above 20 divisions, a reading was taken. If it remained below this level, the selector valve was turned to “medium”, but pressure remained at 0.25 atmospheres. If the float could not rise to the preferred range in either the large or the medium tubes, the selector valve was turned to “small”. When the proper flowmeter tube had been determined by the above procedure, reading was taken to the nearest division. Often time the float may swing in a small range. In such cases, an estimation of the float range center would be taken.

The pressure was kept at 0.25 atmospheres. Although the pressure could be increased to 0.5 and 1.0 atmosphere, in the experiment it was found that the high pressure might break the soil sample, producing artifacts. The pressure applied on the soil sample was, therefore, kept low. Before every experiment, the entire system must be checked for leakage. A steel cylindrical sample rather than a soil sample was put into the coreholder and repeated the procedure described above. If zero reading was taken from the flowmeter, the experiment continued. If there was any positive reading, the entire system had to be checked for leakage.

In some of the tests, deviatoric loads were applied on the soil samples. After sealing the core soil sample, put it in the chamber as shown in Figure 3.4.1 and made sure that the sample was hold tightly. Froze the sample to the required temperature. Then applied the required pressure on the sample. The procedure for permeability test mentioned above was then followed to obtain a reading.

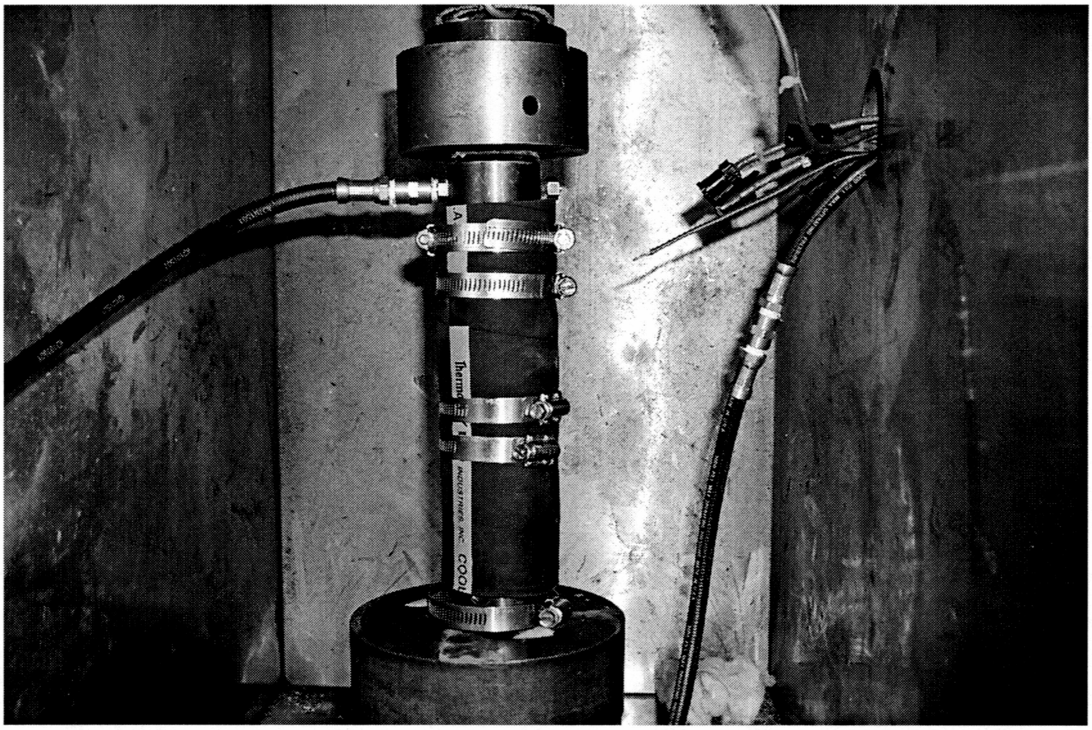


Figure 3.4.1 A Soil Sample under Applied Axial Load

The applied load may change the texture of the sample. A constant pressure was maintained during the test for a sample. The hydraulic loading system uses a load cell to control the loads and the temperature variation has a significant impact on the load cell. In addition, it induced creep of the pressure changes with the temperature. It was difficult to maintain the constant level of the pressure due to very low magnitude of the pressure as compared to the capacity of the loading frame. In many cases, the load had to be released at a temperature and applied again at a changed temperature.

Chapter 4

Experiment Results and Analysis

A number of gas dissemination experiments were conducted in the Rock Mechanics Laboratory of the Department of Mining and Geological Engineering, University of Alaska Fairbanks. In the experiments, ground temperature, moisture content and the applied load were the three parameters considered to have major influence on the gas permeability. The laboratory experiments were designed to be conduced over a range of these parameters.

4.1 Experiment Procedure

The experiments were conducted under different temperature, moisture content and axial loading conditions. The experiment procedure is given below.

(1) Prepared soil samples using the method discussed in chapter 3 with the water content at a pre-designed level, for example, 15%. Because of the limitation of the experimental apparatus, especially the accuracy of the gas permeameter, the gas permeability of soil samples with moisture content higher than 20% cannot be measured directly with the permeameter.

(2) Set up the equipment and inspected the system for possible leakage in the system. For system checking, a steel cylinder was used to replace the soil sample. The steel cylinder was considered to have zero permeability. If there was any positive reading from the flowmeter, the entire system had to be examined till no leakage can be detected.

(3) Installed the soil sample in the core-holder and placed it into the cold (environmental) chamber. The cooling system was then started. Waited and allowed the temperature to fall down to the pre-designed temperature and kept the temperature steady for about half an hour, then measured the permeability using the operation procedure presented in chapter 3. The experiments were repeated at every pre-designed temperature level. In order to make sure the temperature of the soil sample was at the right temperature, the water temperature in the cooling coil system rather than the air temperature in the chamber was measured and considered to be approximately the same as that inside the soil sample. Since the soil sample was sealed in the system, it was very difficult to measure the temperature in the soil sample directly. However, there were still some limitations by measuring the water temperature in the cooling coil system. It was found that the water temperature was slightly different at different depths. The only solution to this problem was to wait a bit longer until the temperature reached its equilibrium or near equilibrium point. Often time, this was very time consuming. Therefore, some small error cannot be avoided with this testing system. It was considered these errors were not significant.

During the experiments, another concern was about the time effect. The soil sample was kept temperature steady for about half an hour in order to make sure the sample was at the set temperature. However, if the sample was kept at the temperature for a longer time, such as more than 24 hours, the results could be different because the free water freezing was also relative to the time of freezing according to cooling theory water and ice in soils.

During the measurement of the permeability at different temperatures, different axial loads were also applied on the soil sample to investigate the effect of earth pressure on the frozen soil permeability. In the experiments, axial loads of 20 psi and 50 psi were applied on the samples employing the hydraulic loading system. This applied load was greater than the actual earth stress experienced in the field. However, the control system could not provide lower load on the samples accurately due to its limitation. To overcome this limitation, dead-weight method was also used. It was designed to run the experiment from low load to high load, but not the other way around. It was considered that when a load applied to a sample, the soil texture would change permanently. Lowering the loading would not be able to recover the changed the texture. In the experiments, the axial loads might be released after a measurement at a temperature, and then were applied again at another temperature, because it was difficult for the hydraulic loading system to maintain the low loads with the change of the temperature.

(4) If the soil sample was thawed and refrozen, there was a change of soil texture or soil structure in soil sample. In the experiment, a couple of the samples were tested with a thaw-and-refreeze cycle to study the change of soil texture. The thaw-and-refreeze cycle was not repeated for many times because the tests were very time-consuming.

(5) Additional two experiments were designed to measure the soil samples whose moisture content was more than 20%. At this moisture content, the gas permeability was very low and could not be measured by the gas permeameter. As special device was developed to conduct the very low permeability measurements. A thin transparent plastic tube was connected to the metal end connector. Oil was injected to seal a section of the tube. When the gas flowed through the soil samples, the volume change of the gas in the tube can be measured to obtain the average flow rate through the soil samples.

The permeability can be obtained using equation (4.1). However, the accuracy of the experiment results cannot be estimated as compared to the results from the permeameter. There were two possible errors existing in the experiments: (1) the volume error. When the nitrogen flowed through the soil sample, the volume of the gas in the tube was changed. Oil that sealed the tube was pushed within the tube. However, some oil still stuck inside wall of the tube. The measurement of the volume change of the gas actually included the volume of the sticking oil. The measurement of volume change was not very accurate; (2) the time error. In order to calculate the average flow rate of the gas, the time difference of the volume change was also measured. There was error in the measurement of the time. It was within 10 seconds over a measuring time in the order of several minutes.

The equipments for very low permeability experiments are shown in Figures 4.1.1 and 4.1.2

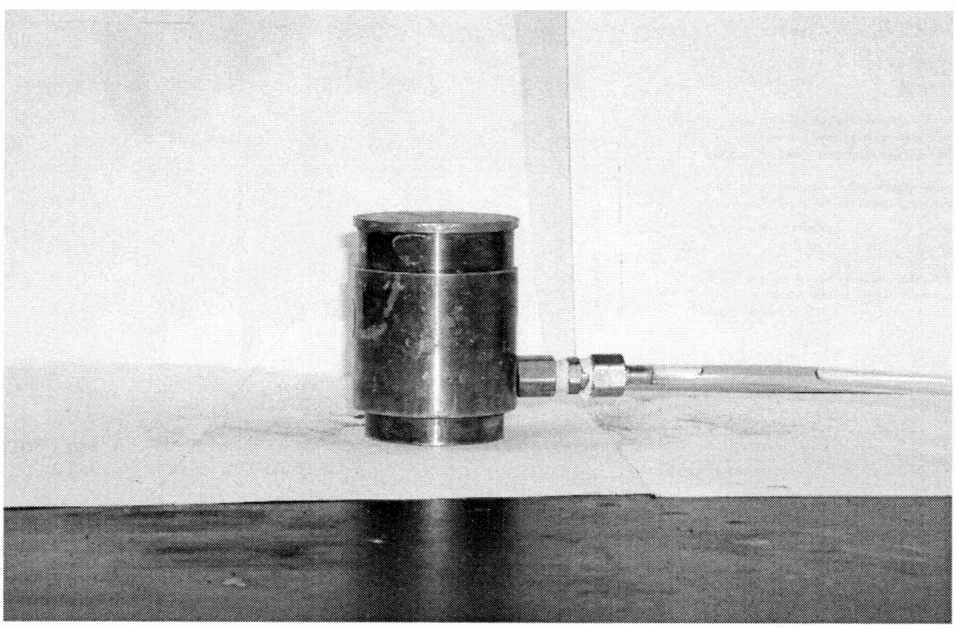


Figure 4.1.1 Metal End Connector

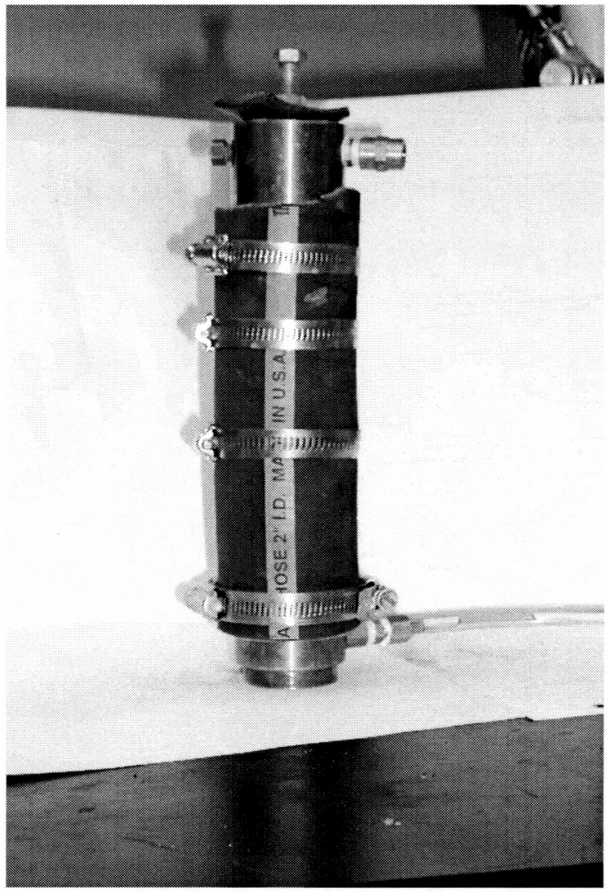


Figure 4.1.2 The Set-up of the Equipment

In 1941, Klinkenberg reported variations in permeability determined by using gases as the flowing fluids, which were considered to be due to slippage; Many engineers and researchers conducted the experiments to study the effect of gas slippage, particularly in reservoir engineering. However, few experimental data regarding the gas slip effect of gas dispersion in frozen ground are published. There may be significant effect of gas slippage in the permafrost. Because the research of gas dispersion in frozen ground is still in its primacy phase, the experiments conducted in this study are to measure the apparent gas permeability kg. The main difficulties in measuring Klinkenberg effect arise from the following aspects: (1) significant mass transfer between the phases when the soil sample is frozen and the water in the sample changes to ice. (2) The texture of the frozen soil is changing with varying temperature. (3) The structure of the frozen soil varies with other factors, for example, the different moisture contents. Because of limitation of the equipment, the microstructure of the frozen soil sample cannot be observed. It is very difficult to estimate the Klinkenberg effect with the equipment available in this study.

In reservoir engineering research, gas slippage in a single-phase gas flow in different rocks has been investigated extensively. Counsil (1979) discussed gas slip effect and showed that the effect of gas slippage was small when b = 0.2 atm and Pmean = 10 atm (b is a constant and Pmean is an average pore pressure for the gas). Therefore, the gas slip effect was not considered in the analysis of the gas flow data. He stated that: "For the case of stream-water relative permeabilities, slip could be reduced by running experiments at very high pressures, and very high temperatures." However, the experiments in this study require low temperature and relatively low pressure. The gas slippage may have an impact on the laboratory experiments.

In the experiments, however, the effect of gas slippage cannot be estimated because of the limitation of the equipments. It is recommended that gas slippage be measured for in-depth study in the future.

4.2 Calculation of the Permeability

After taking the reading from the flowmeter, the following formula used for calculating permeability:

$$K=(\mu QL)/(AP) \qquad (4.1)$$

Where:

K = Permeability in darcys

μ = Viscosity in centipoises of the gas (nitrogen) used for making the measurements at the observed temperature (as shown in Figure 4.2.1)

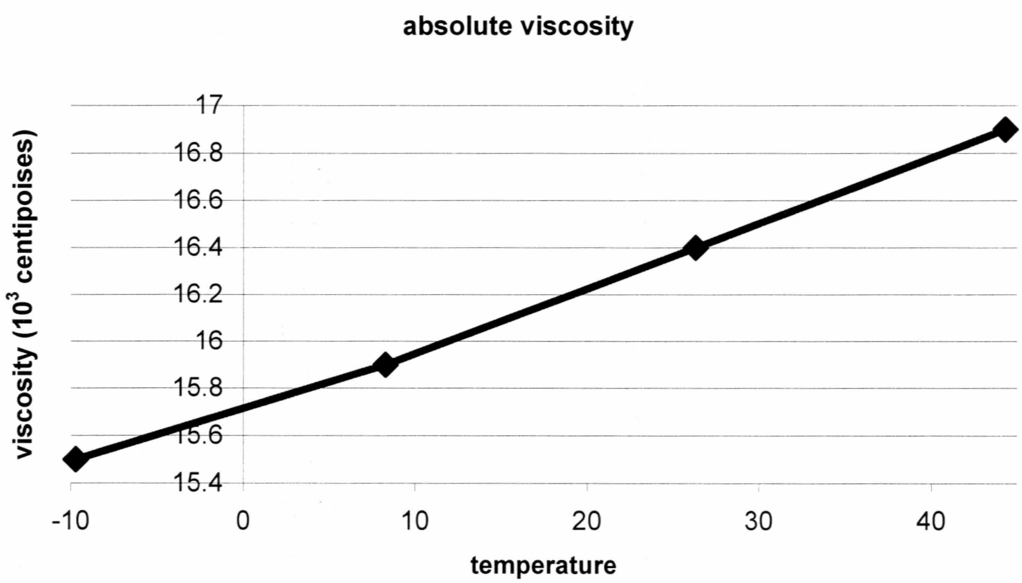


Figure 4.2.1 Absolute Viscosity of Nitrogen

Q = Average flow rate in cc/second in the sample at mean pressure derived from the flowmeter reading and calibration curve of the flowmeter.

L = Length of sample in centimeters.

A = Cross-sectional area of sample in square centimeters.

P = Pressure gradient in atmosphere, indicated by the pressure gage.

4.3 The Experiment Results and Analysis

4.3.1 Basic Properties of Soil

Seventeen soil samples were tested in the laboratory study. Soil is silt to sandy silt, mostly between 0.001 and 0.1mm in size. The organic contents of the soils range from 1.8% to 9.9%, with an average of 4.8%. The moisture contents of soil samples ranged from 5% to 25%, with bulk density from 80 (pound/cube ft) to 120 (pound/cube ft), degree of saturation of samples ranging from 10% to 80% and porosity of samples at about 52%. The relationship between the moisture content and the above three properties are shown as the Figures 4.3.a through Figure 4.3.c.

The soil was remolded to obtain the reproducibility of the samples. Although the proctor compaction test is developed to deliver a standard amount of mechanical energy to determine the maximum dry unit weight of a soil, the preparation procedure of the soil sample keeps the uniformity of the samples. Based on the test results of the basic properties (bulk density, degree of saturation and porosity), the diversity of the soil samples seemed relatively small. However, these are the properties for unfrozen soils. For frozen soils, they could be different that may be potentially due to fracture development in the soil. Bulk density and porosity are of special importance in considering the frost susceptibility of soils. The porosity is close to a constant before the soil gets fully saturated, when the soil is unfrozen. However, when the soil freezes, porosity may be a function of the temperature. It is recommended that more in-depth experiment be conducted to measure the porosity at different temperatures.

Table 4.1 Bulk Densities and Moisture Contents

Moisture Content	5.50%	5.8%	8.8%	9.9%	10.0%	11.7%	13.9%	17.6%	19.5%	23.80%	25.0%
Bulk Density (pound/ft3)	86.9	81.9	96.1	92.7	94.5	108.9	102.2	107.7	123.5	108.0	108.2

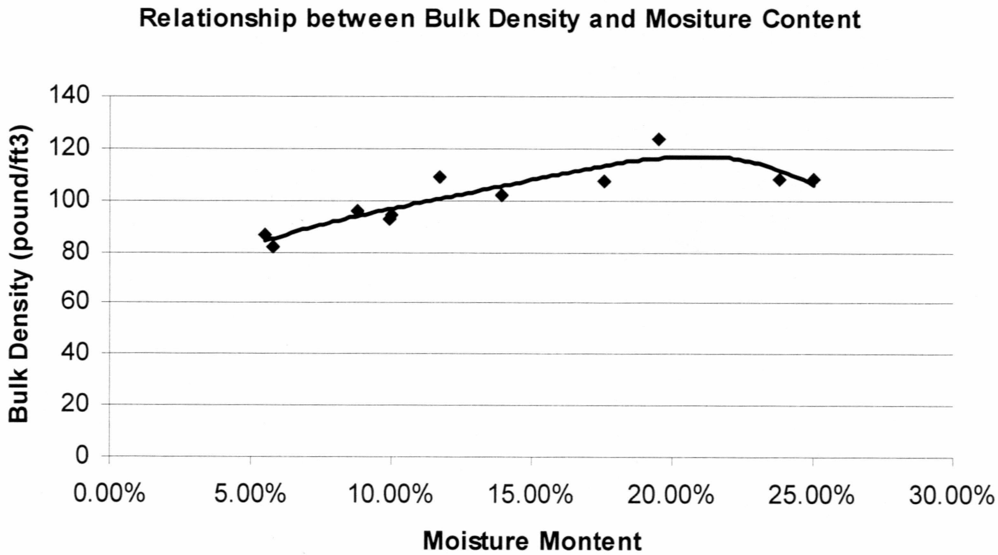


Figure 4.3.a Bulk Density and Moisture Content

Table 4.2 Degree of Saturations and Moisture Contents

Moisture Content	5.50%	5.8%	8.8%	9.9%	10.0%	11.7%	13.9%	17.6%	19.5%	23.80%	25.0%
Degree of Saturation (%)	13.2	12.5	24.2	25.1	48.9	39.6	39.6	52.1	75.1	75.5	78.1

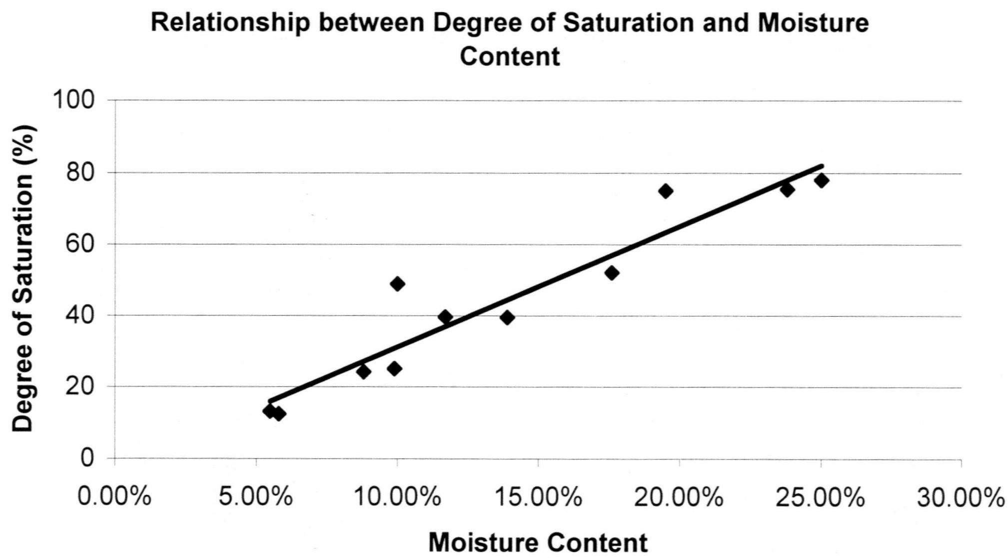


Figure 4.3.b Degree of Saturation and Moisture Content

Table 4.3 Porosities and Moisture Contents

Moisture Content	5.50%	5.8%	8.8%	9.9%	10.0%	11.7%	13.9%	17.6%	23.80%	25.0%
Porosity (%)	54.6	57.3	51.3	53.5	57.6	46.2	50.5	46.2	54.6	55.2

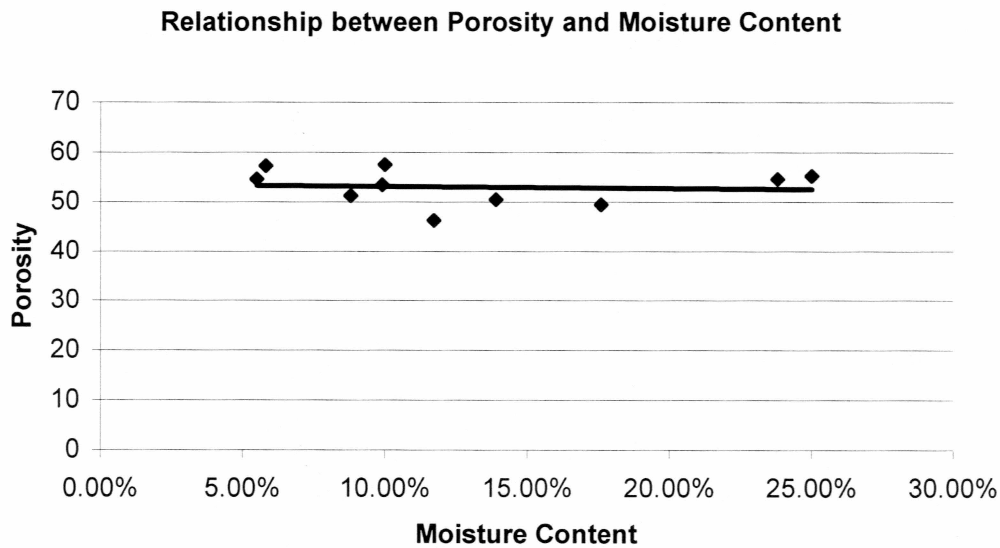


Figure 4.3.c Porosity and Moisture Content

The experiment results were divided into three groups: (1) Permeability vs. Temperature at different known moisture contents; (2) Permeability vs. Moisture Content at different temperatures; (3) Permeability vs. Applied Loads at different temperatures and moisture contents. The results are given below.

4.3.2 Permeability Vs. Temperature at Different Known Moisture Contents

A number of tests were conducted to examine the permeability variation as a function of temperature at a given moisture content. They are described below.

Test A: Moisture content of soil sample was set at 5.8% and an axial load of 50psi was applied on the soil sample throughout the test. The temperature in experiment was from 25°F to –10°F. Figure 4.3.1 shows the results.

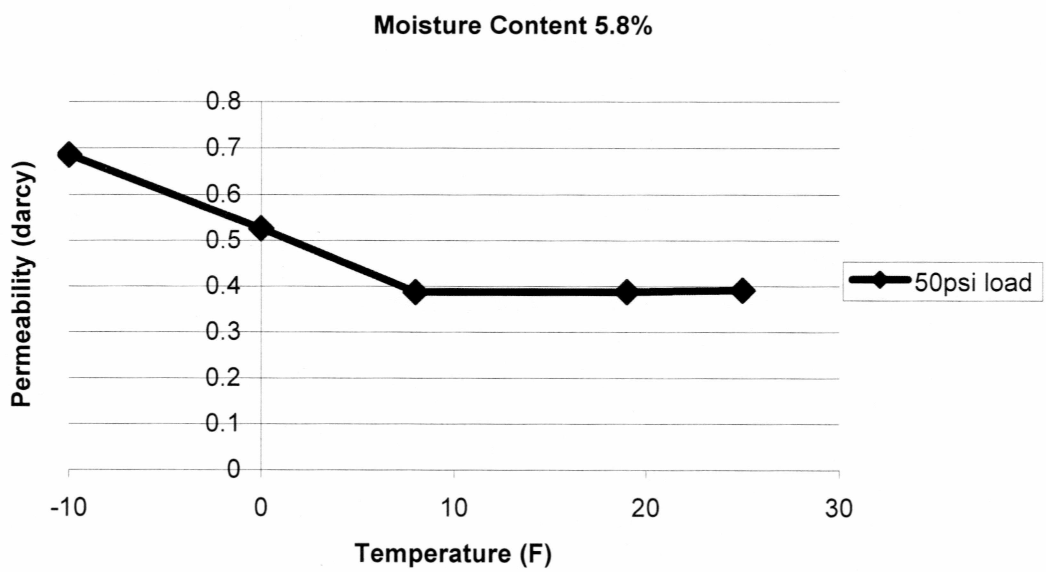


Figure 4.3.1 Permeability vs. Temperature at Moisture Content 5.8%

Test B: Moisture content of soil sample was set at 8.8%. There was no load applied on the sample at the beginning (temperature 28°F). When the temperature fell to 15°F, an axial load of 50 psi was applied and maintained on the sample. The permeability experiment was repeated until the temperature dropped to 4°F. After that, the temperature was allowed to rise and the experiment was repeated until the temperature reached 27°F. The results of this experiment are shown in Figure 4.3.2.

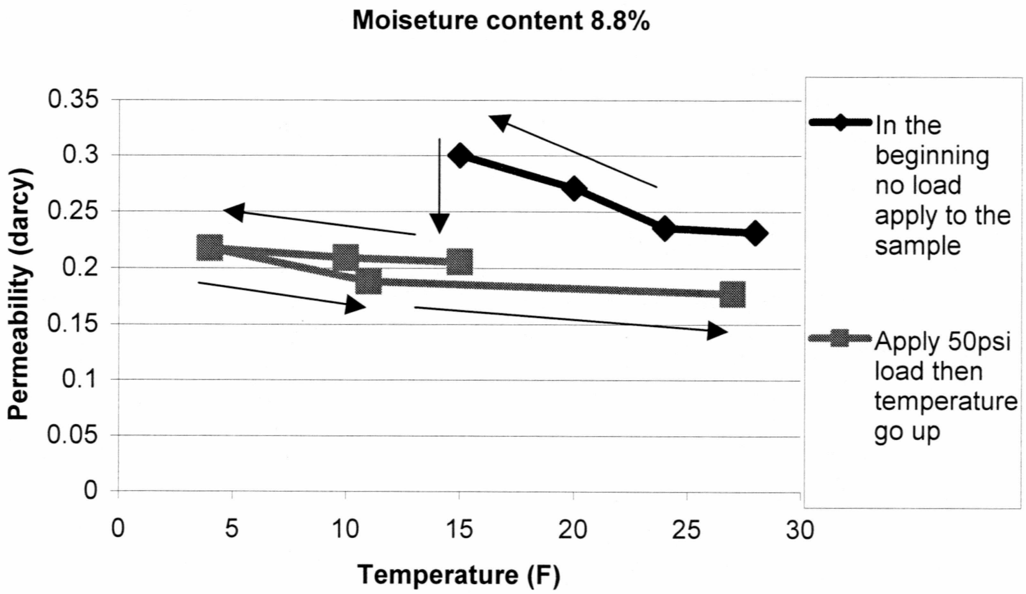


Figure 4.3.2 Permeability vs. Temperature at Moisture Content 8.8%

(The arrows indicate the timing sequence in the tests)

The measurement process of this soil sample experiment reflected the stages of the characteristics of gas permeability in frozen soil being revealed and understood. In the beginning, it was reasonable to assume that the permeability would fall with the temperature decreased. However, the observation was that the permeability went up after the temperature dropped to 22°F. The axial load was then applied on the sample and the permeability fell about 30%. However, the permeability rose again with lowering temperature although the load was maintained at 50 psi. At the final stage, the experiment continued with an increase of the temperature in order to estimate the effect of the thaw-and-refreeze to the soil sample.

Test C: Moisture content of soil sample was set at 9.9% and an axial load of 50 psi load was applied on the soil sample. The temperature in experiment was from 24°F to 6°F. The results are shown in Figure 4.3.3

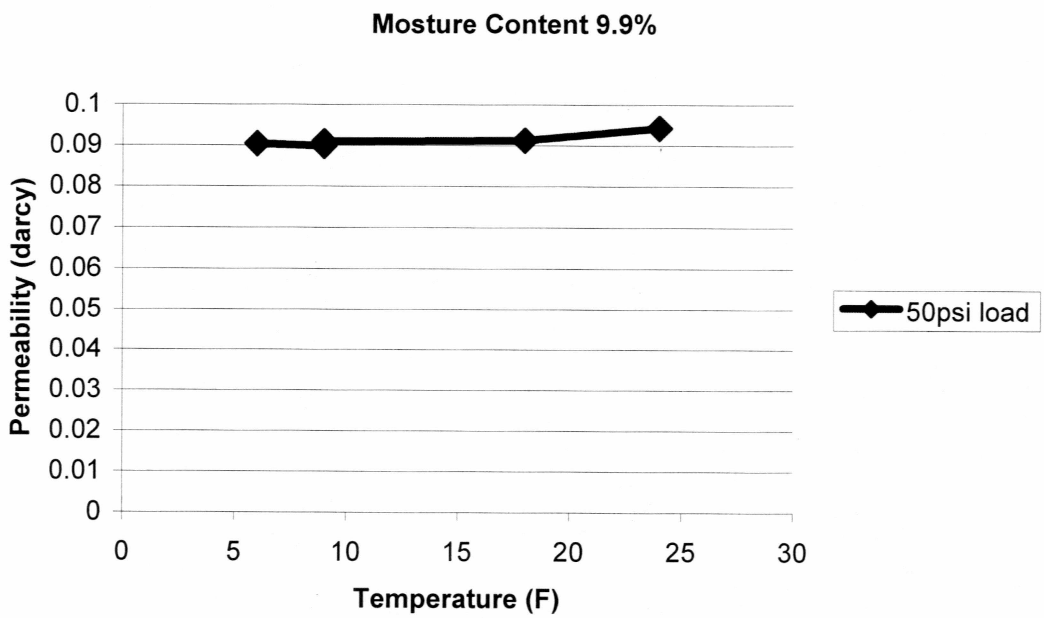


Figure 4.3.3 Permeability vs. Temperature at Moisture Content 9.9%

Test D: Two soil samples were prepared with 10% of moisture content. Tests were conducted on Sample 1 with no load applied. The temperature in experiment was from 24°F to 0°F. The sample was then allowed to thaw and was refrozen on the second day. Testes were repeated on the refrozen sample (The temperature in experiment was from 28°F to 0°F). A 50psi load was applied on Sample 2 and tests were conducted at temperatures ranging from 29°F to 7°F. The results are shown in Figure 4.3.4.

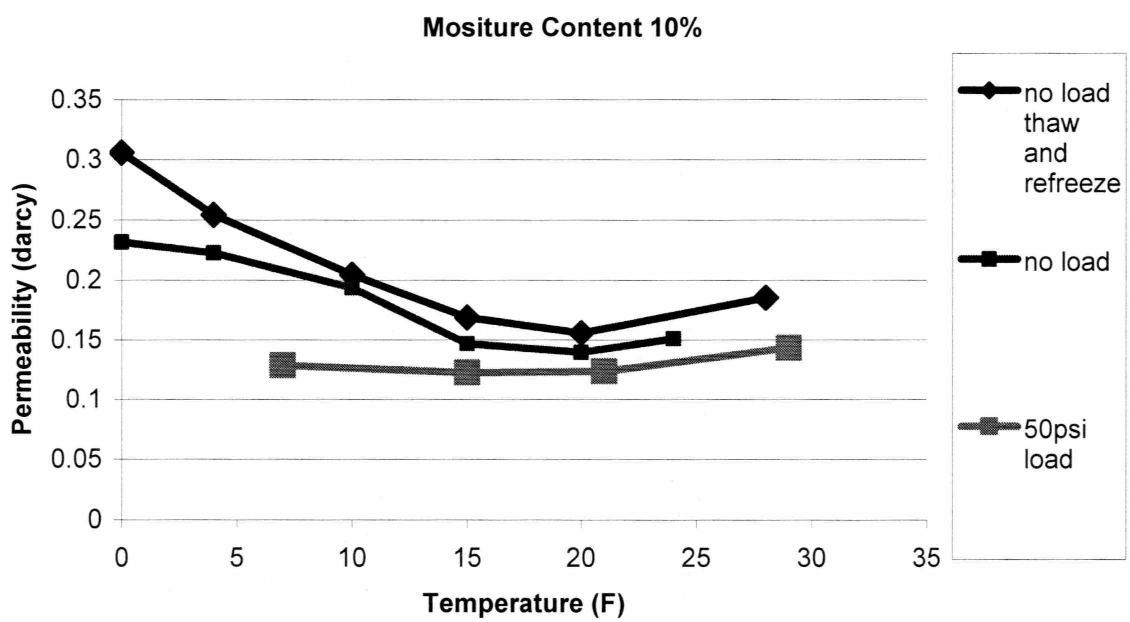


Figure 4.3.4 Permeability vs. Temperature at Moisture Content 10.0%

Test E: Moisture content of soil sample was set at 11.7% and a load of 50psi load was applied on the sample from 29°F to 2°F. The experiment was repeated on the thawed and refrozen sample, maintaining a 50psi load from 26°F to -1°F. The results are shown in Figure 4.3.5.

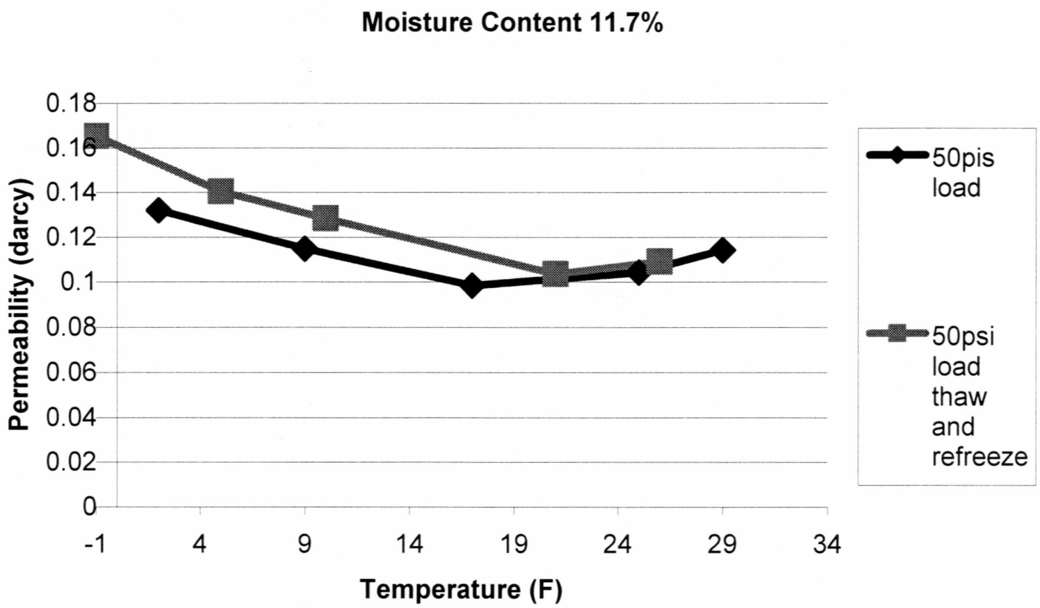


Figure 4.3.5 Permeability vs. Temperature at Moisture Content 11.7%

Test F: Moisture content of soil sample was set at 12.7%. There was no load applied on the sample from 28°F to 6°F during the first run. In the second day, the experiment was repeated at temperatures ranging from 28°F to 10°F when the sample was thawed and refrozen. The temperature was then raised to 15°F and a 50-psi load was applied on the sample to continue the experiment. During this experiment, the 50-psi load was released and reloaded on the sample at 9°F. Figure 4.3.6 shows the results.

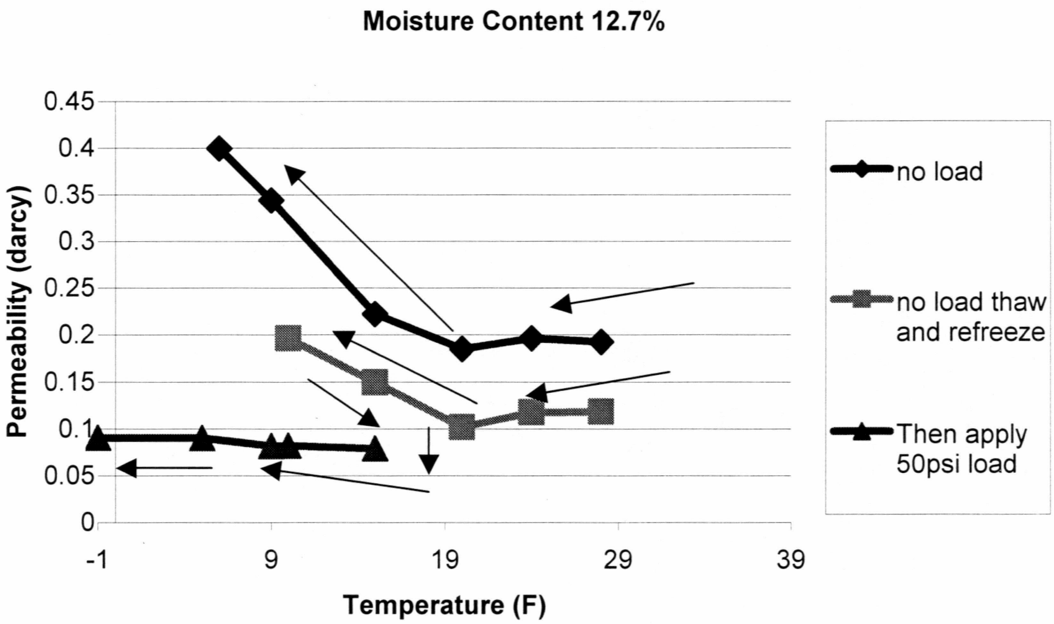


Figure 4.3.6 Permeability vs. Temperature at Moisture Content 12.7%

(The arrows indicate the timing sequence in the tests)

Test G: Moisture content of soil sample was set at 19.5%. There was no load applied on the sample from 28°F to 0°F. The sample was then thawed and refrozen and the experiment repeated from 27°F to 0°F. The results are shown in Figure 4.3.7.

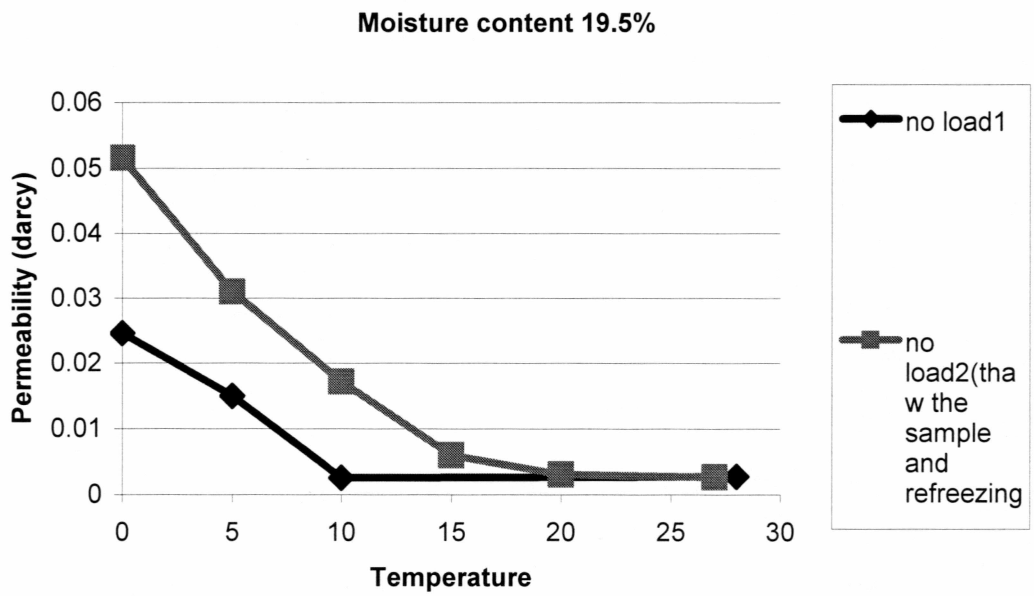


Figure 4.3.7 Permeability vs. Temperature at Moisture Content 19.5%

Test H: Additional experiments were conducted in the laboratory to test very low gas permeability of frozen soil when the moisture content was above 20%. A specially designed device that was introduced previously was used. The moisture contents were set at 23.8% and 25%. There was no load applied on the samples. The temperature of the samples of 23.8% was from 25°F to 11°F. The temperature of the samples of 25.0% was from 25°F to 14°F. The gas volume change in a plastic tube was measured to calculate the flow rate and the permeability. The results are showed in Figures 4.3.8 and 4.3.9.

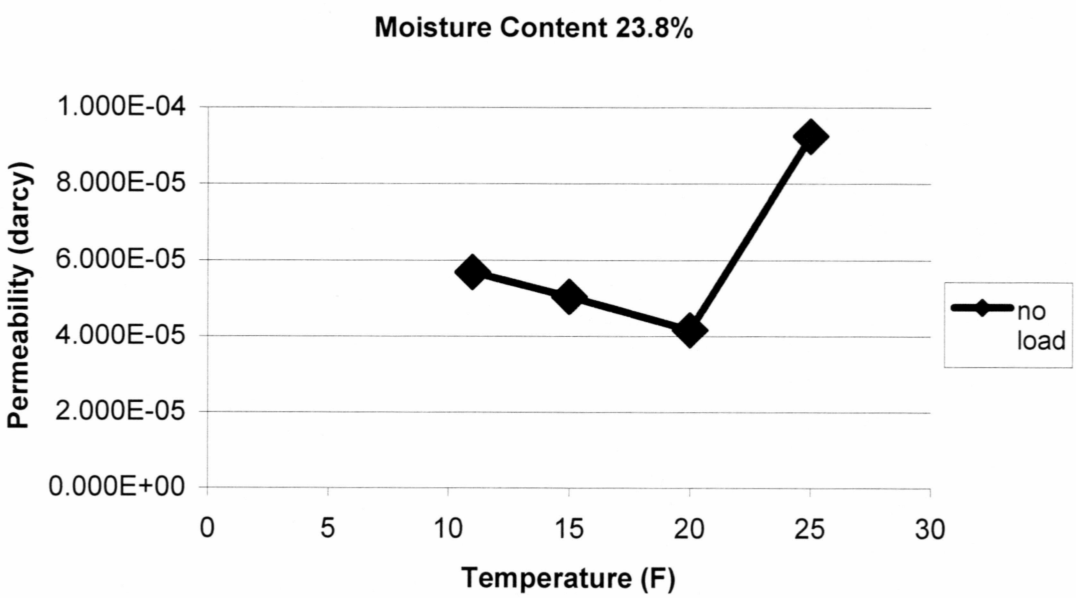


Figure 4.3.8 Permeability vs. Temperature at Moisture Content 23.8%

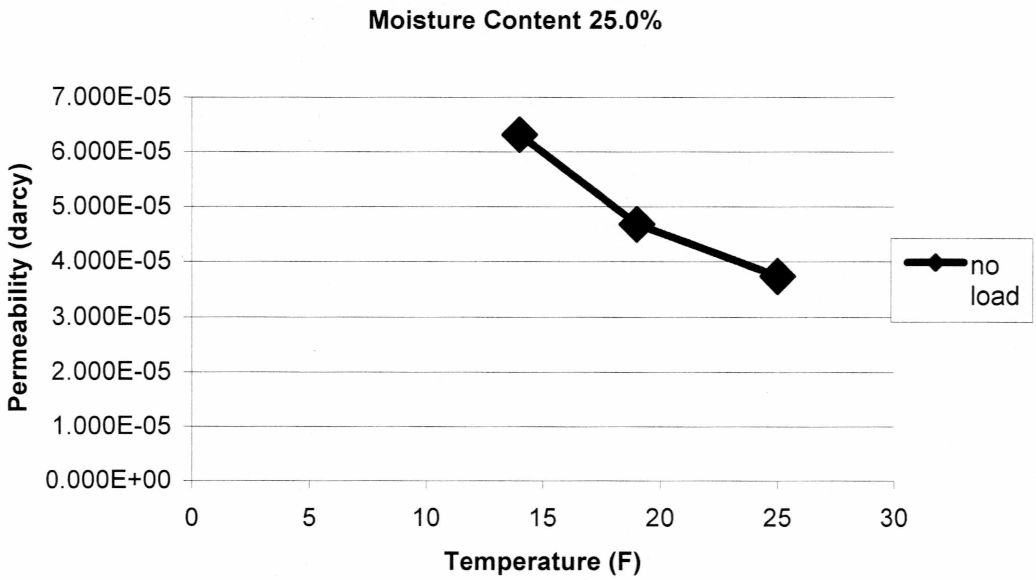
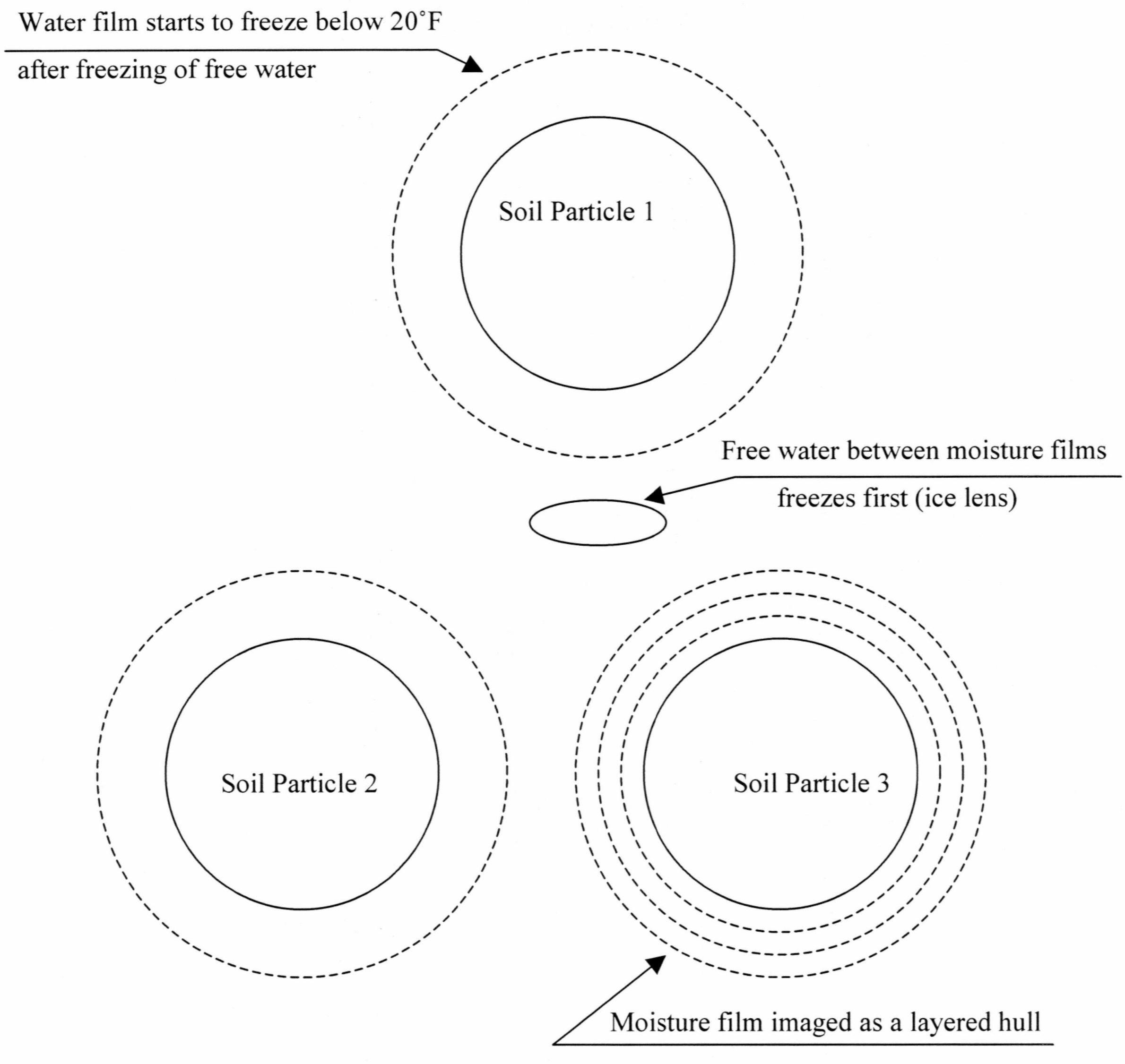


Figure 4.3.9 Permeability vs. Temperature at Moisture Content 25.0%

The permeability of frozen soil is temperature dependent. The temperature variation can change the texture of the frozen soil. The ice content, which is an important physical property of the frozen soil, is a function of the temperature. It is logical to assume that temperature plays an important role in the gas dispersion behavior in frozen ground. It shows evidently from Figures 4.3.1 to 4.3.9 that at different applied loads, the effects of temperature, ranging from 0°F to 30°F, are significant.

The results of the experiments also reveal that permeability decreases with temperature falls within the range of 30°F to about 20°F. When the temperature drops further to below 20°F, however, an increase in permeability was measured. There are two possible explanations for observations although no concrete conclusions can be drawn at this point due to inability of examining the microstructures of frozen soils.

One possible reason (Explanation I) is that the volume of soil sample was enlarged because the density of the ice is smaller than that of unfrozen water. According to the cooling theory for water and ice in soils, unfrozen water (free water and bound water or water film) usually coexist simultaneously in frozen soil and have different freezing points. At close to 32°F, the free water in bulk in the voids of the soil is the first type of soil water to freeze. The less-stressed water films (farther away from the surface of the soil solid particle) freeze next, and the freezing front continues to move towards more stressed area. Therefore, not all the water freezes when soils are subjected to freezing temperatures. A considerable amount of unfrozen water is still contained in the soils. The pore water does not start to freeze until the temperature drops further. With the temperature falls, more water changes to ice. It is considered that most of the free water changed to ice at 20°F in the period of experiments. The bound water started to freeze below 20°F after the freezing of free water. The water filming on the soil particle surface freezes in layers. The most outside layer freezes first while inner layers are still in liquid form surrounded by ice. The inner layers are subjected to a more intense contraction because of the enlarged volume of outside layer ice. As water films change to ice, the volume of the soil particle and water film is enlarged. Therefore, the specific surface area of the particles becomes smaller as compared to that of the particles with a smaller volume, as shown in Figure 4.3.10. With a smaller specific surface area, the gas flowing through the particles has less contact area per unit volume, thus less resistance. This results in a higher permeability. Although the soil sample was sealed tightly, there was still some room for sample to expand. It was designed that the end holder could move with the volume change of the sample in the experiments. Therefore, the soil sample could expand freely. The microstructures of the soil sample could not be observed in the current study due to the limitation of the equipments. More in-depth studies that allow detailed interior observation of the samples are recommended to confirm this assumption.



The specific surface of particles (including both soil and water film) becomes smaller as compared to that of the particles with a smaller volume

Figure 4.3.10 Freezing of Soil Moisture

Another possible reason (Explanation II) is that the soil sample may have had fractures or micro-fracture developed as the temperature drops below 20°F. The higher permeability is due to the development of the fracture in the soil. At present time, the behaviors of partially saturated frozen soils is not well understood by most researchers. Most theories of the frost heave is developed based on full saturation of soils. There are still many un-knows and debates on the theories for partially saturated frozen soils. This explanation does not attempt to explain the the microstructure and the behavior of partially saturated soils, but presents a possible interpretation for the phenomena observed in the experiments.

In a real engineering situation, the field site of the gas pipeline is more complicated than the laboratory. The difference of the temperature between the daytime and nighttime will cause more significant development of fractures in the frozen soil. It is even possible to have moving free water in the frozen soil because of the diversity of the moisture content in frozen ground and the groundwater in the field. When the water moves, the micro-fracture may also be developed. It is likely that higher permeability might be observed in the field and the gas could flow through the frozen ground faster.

The permeability of the frozen soil is most likely affected by the microstructure of the soil. If the soil was thawed and frozen again, there could be a significant change of the soil texture or the microstructure of the soil. In the experiments, several samples were tested with a thaw-and-refreeze cycle. All the samples except one (Figure 4.3.6) showed a higher permeability after a thaw-and-refreeze cycle. Figure 4.3.5 shows even when the soil sample was under 50 psi load, a higher permeability was obtained after a thaw-and-refreeze cycle. Konrad (1989) has reported that repeated freezing and thawing of clayey soils would produce an increase in the effective void ratio. Smith and Porkhaev (1972) also observed that freezing and thawing increased the permeability of fine-grained soils. The thaw-and-refreeze cycle in the experiments is considered to increase the effective void ratio, which causes an increase in the permeability.

4.3.3 Permeability Vs Moisture Content at Different Temperatures

A: The curves of permeability vs. moisture content at different temperatures are shown in Figures 4.3.11 and 4.3.12.

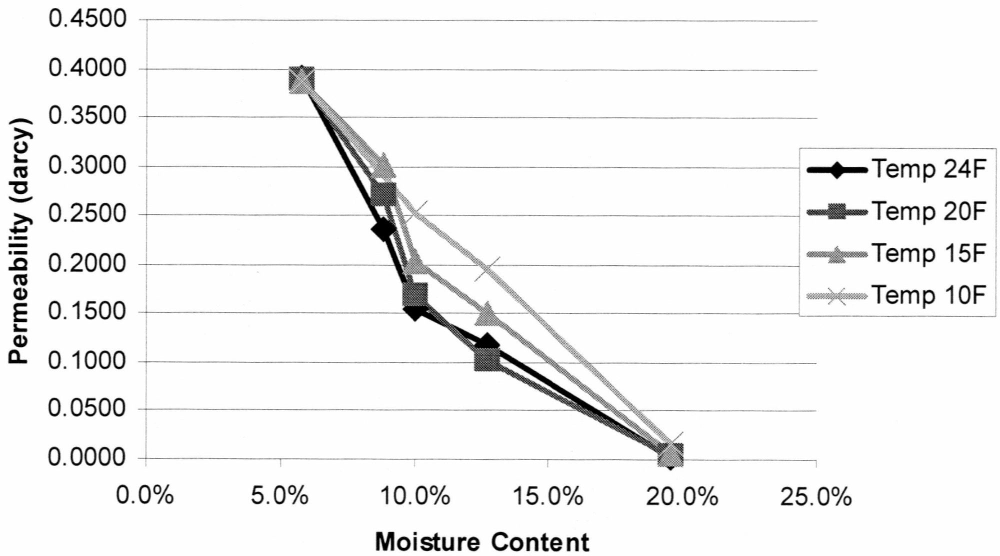


Figure 4.3.11 Permeability vs. Moisture Content at Different Temperature

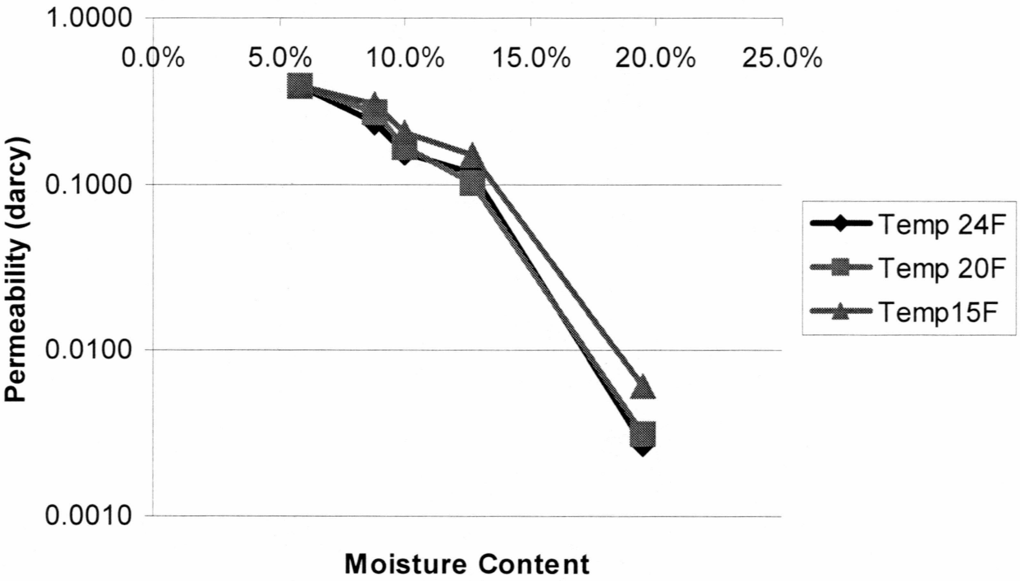


Figure 4.3.12 Permeability vs. Moisture Content at Different Temperatures

Figure 4.3.11 is a normal scale of the permeability and Figure 4.3.12 is a logarithmic scale of the permeability.

B: Figures 4.3.13 and 4.3.14 show the curves of permeability vs. moisture content at temperatures 15°F and 10°F respectively with and without a 50-psi load.

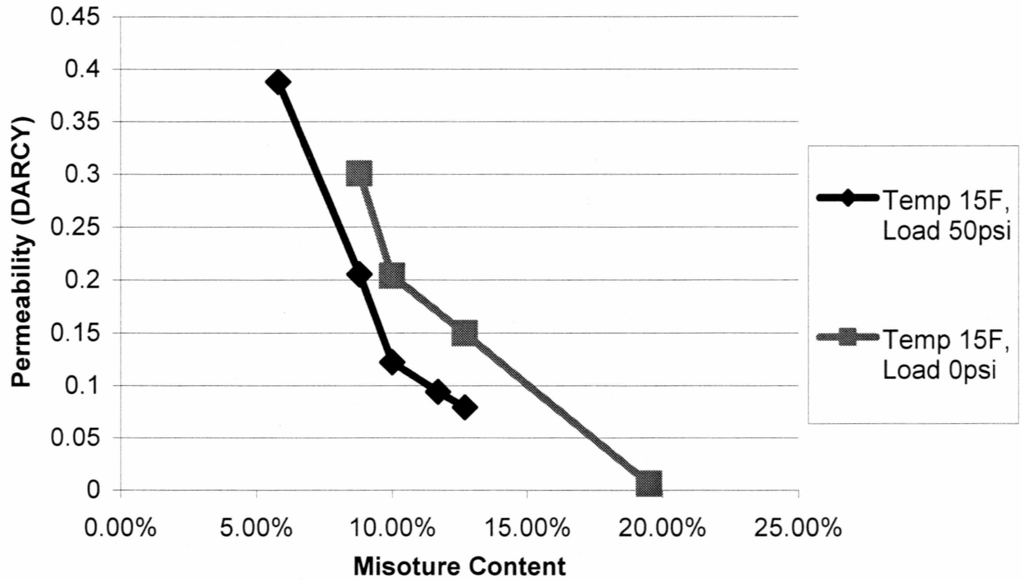


Figure 4.3.13 Permeability vs. Moisture Content at Temperature 15°F with Different Loads

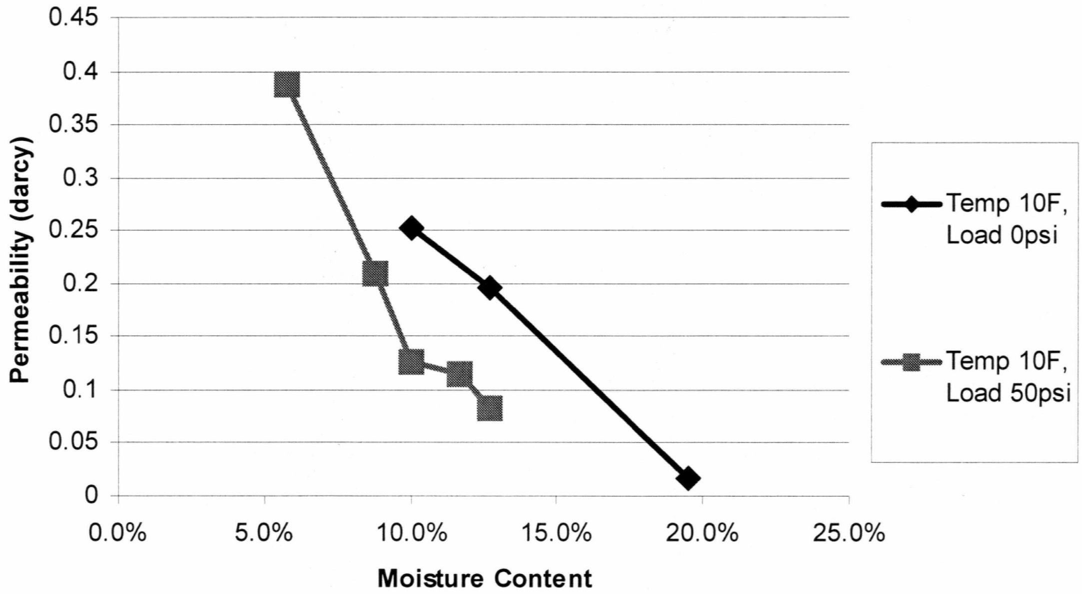


Figure 4.3.14 Permeability vs. Moisture Content at Temperature 10°F with Different Loads

C: Figures 4.3.15 and 4.3.16 show the permeability vs. moisture content curves at different temperatures (15°F, 10°F, 5°F, 0°F) with a 50-psi load.

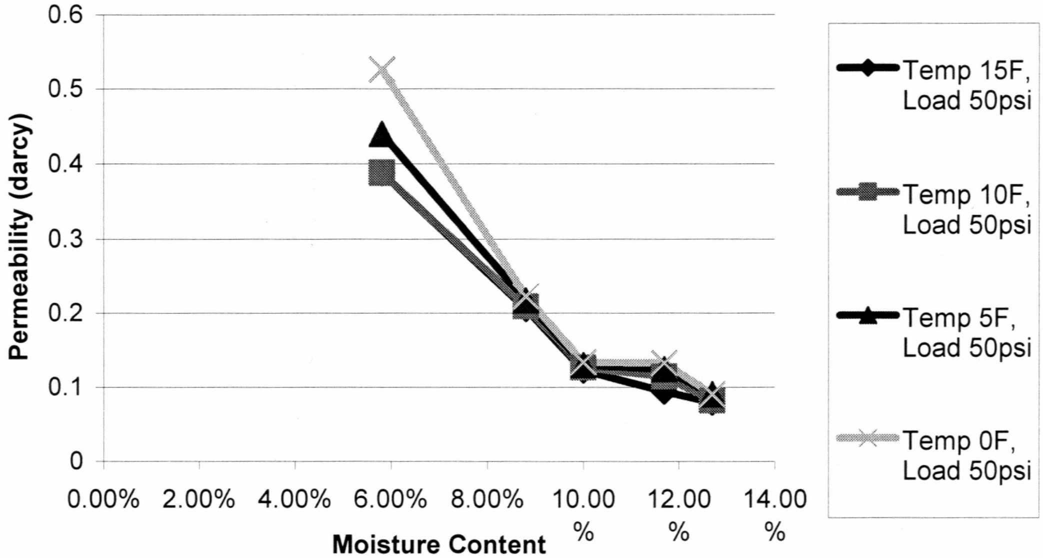


Figure 4.3.15 Permeability vs. Moisture Content at Different Temperatures with 50 psi Load

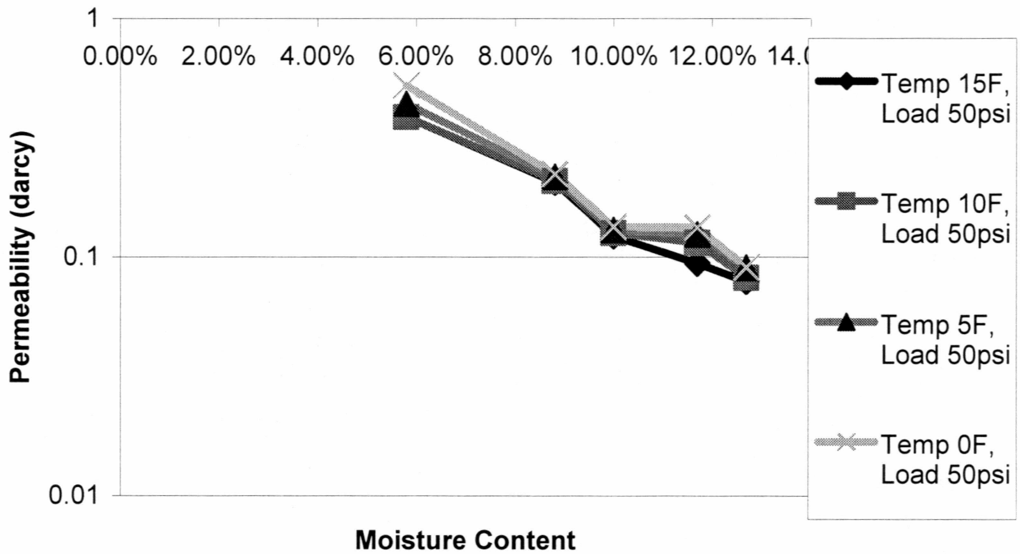


Figure 4.3.16 Permeability vs. Moisture Content at Different Temperatures with 50 psi Load

Figure 4.3.15 is a normal scale of the permeability and Figure 4.3.16 is a logarithmic scale of the permeability.

The most fundamental difference between frozen soil and normal soil is the presence of ice in the frozen soil. Frozen ground contains ice in several forms, ranging from coatings on individual soil particles and small lenses to large inclusions and massive deposits. Previous research (Andersland and Anderson, 1994, An Introduction to Frozen Ground Engineering) already shows that unfrozen clean sand and gravel mixtures will have a permeability (water conductivity) approaching 1cm/s (864m/day), permeability (water conductivity) of the same saturate soil in the frozen condition will approach zero.

The experiment data from Figures 4.3.11 to 4.3.16 also show that moisture/ice content has significant impact on the gas dissemination in frozen ground. As a typical example, Figure 4.3.11 shows the permeability vs. moisture content curves at the different temperatures. When the moisture content increased from 5.8% to 19.5% at a temperature of 24°F, the permeability decreased from 0.3917 darcy to 0.0027 darcy. At another temperature, the permeability also decreases with the moisture content increases. Figure 4.3.13 shows that with a load applied on the soil samples, the permeability still decreases with increase of moisture content.

From the view point of material science, frozen soil is a natural particulate composite, composed of four different constituents: solid grains, ice, unfrozen water, and gas. As mentioned above, until the soil is cooled down to a very low temperature, some of the unfrozen water still exists in the soil pores. Despite the presence of unfrozen water, when ice fills most of the pore space, the behavior of frozen soil, particularly the mechanical behavior, will reflect closely that of the ice. Since the gas permeability of ice approaches zero, the higher moisture content the soil has, the more water freezes to the ice at low temperature. The more pore ice binds the grains together and fills the pore space, the more difficult the gas flow through the soil sample, resulting in lower permeability in the soil sample. Therefore, the permeability decreases with increasing moisture content.

In the experiments conducted in this study, all the permeability vs. moisture content curves show that around 10% of moisture contents is a turning point. From the figures, the slopes of the curves at lower moisture contents are greater than that those of higher moisture contents. In other words, if the moisture content is lower, the permeability changes more significantly as moisture content changes than those with higher moisture contents. For example, in Figure 4.3.11, the curve shows that at 24°F the difference of the permeability from about 5.8% to 10% of moisture content is 0.14 darcy and the difference of the permeability from 10% to 15% of moisture content is only 0.08 darcy. It is considered that there is a transition zone to the soil. The zone could be around the moisture content of 10%. When the moisture content is less than 10%, the unfrozen water freezes faster and the pore ice fills the pore space faster. However, if the moisture content is more than 10%, the rate of freezing and pore icing will be lower and the change of permeability will be smaller. More in-depth study with higher accuracy and more data points may show that the transition zone is a smooth range not a single turning point.

An important finding is that the temperature is not a significant factor that affects the gas dispersion in frozen ground as compared to moisture content. In fact, the permeability of frozen soils depends, to a great degree, on the pore ice existence in frozen soils. Different moisture contents might cause more difference in the ice contents as compared to different temperatures. Therefore, the moisture content is the most significant factor. However, because most of the soil samples tested in this study had less than 20% of moisture content, soils whose moisture content is much greater than 20% may show different characteristics. As mentioned above, there is a transition zone around moisture content of 10%. There may be other transition zones over greater range of moisture contents. When the moisture content is in a much higher range temperature may have more significant impact on the gas permeability of frozen soils.

4.3.4 Permeability Vs Applied Loads at Different Temperatures and Moisture Contents

Additional experiments were performed to examine the impact of ground stress and its induced creep on the characteristics of frozen ground gas permeability. Axial loads up to 50 psi were applied on the soil samples at different temperatures.

A: Figure 4.3.17 shows the relationship between permeability and the applied loads of a soil sample with a moisture content of 13.9% at 7°F.

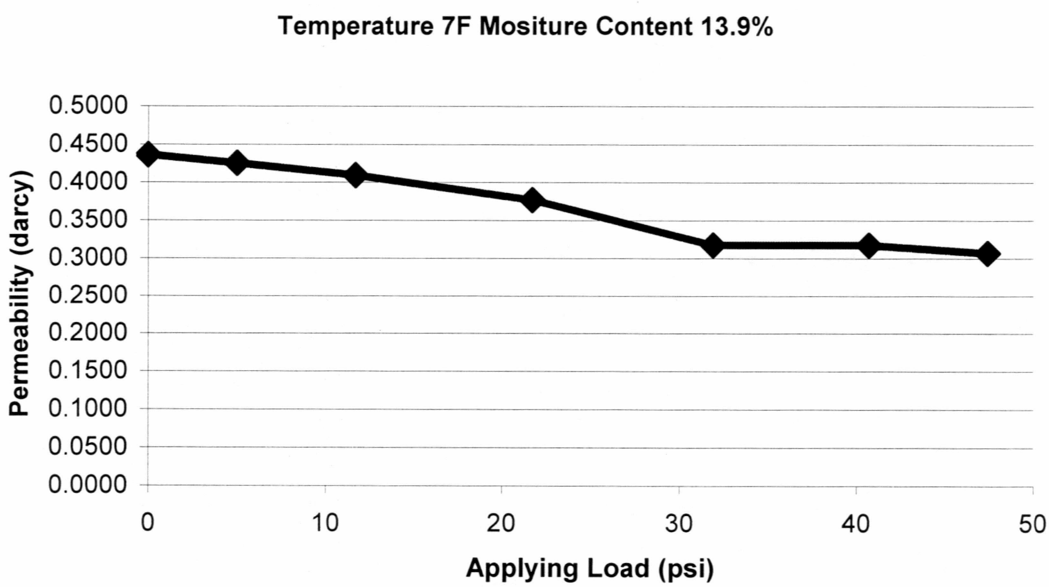


Figure 4.3.17 Permeability vs. Applied Loads at Temperature 7°F with 13.9% Moisture Content

B: Figure 4.3.18 shows the permeability curves of two soil samples with different moisture contents at 17.6% and 5.5% respectively and at temperature 11°F. The applied axial load varied from 0psi to 50psi.

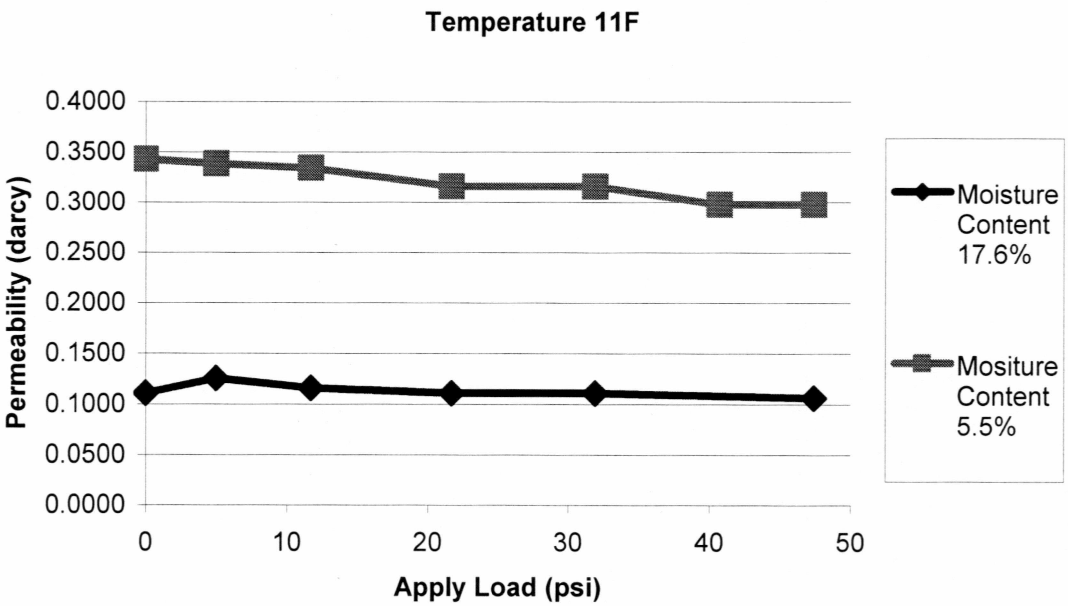


Figure 4.3.18 Permeability vs. Applied Loads at Temperature 11°F with Different Moisture Contents

C: Figure 4.3.19 shows permeability curves of three soil samples under applied axial loads. The samples had moisture contents of 17.6%, 13.9% and 5.5% respectively and were tested at temperatures 7°F and 11°F.

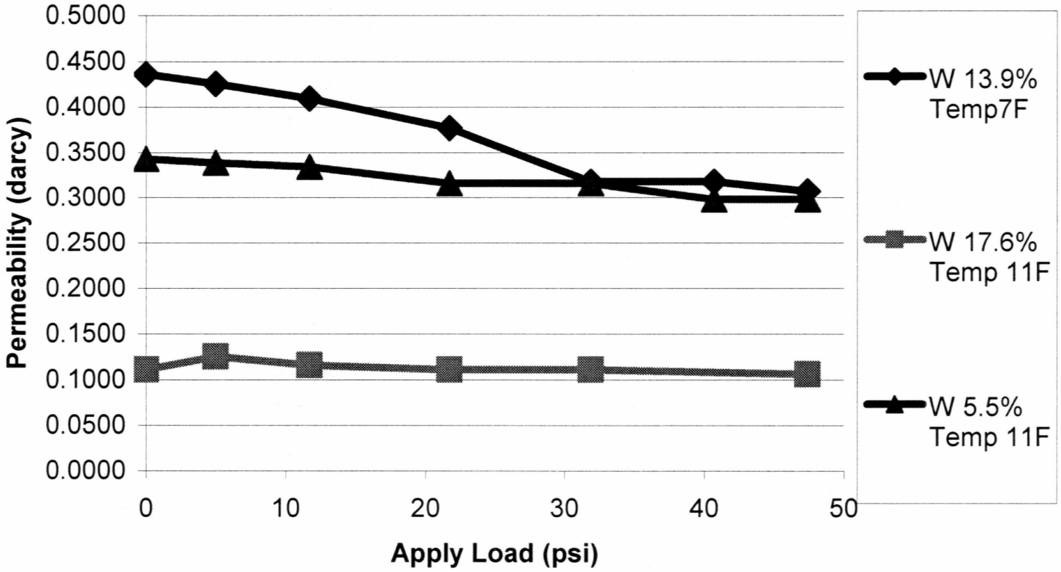


Figure 4.3.19 Permeability vs. Applied Loads at Different Temperatures with Different Moisture Contents

Some of the frozen ground properties are beneficial to engineering projects such as high strength in compression and good bearing capacity. The ice becomes a bonding agent, binding together adjacent soil particles to increase their combined strength and make them impervious to water seepage. The frozen soil has a high strength involving a combination of frictional resistance and interference between soil particles, a dilatancy component, and interaction between the ice matrix and the soil skeleton. When a frozen soil specimen is subjected to a load, it will respond with an instantaneous deformation and a time-dependent deformation - creep. Based on the results of cyclic compression tests on 200-mm cubes of frozen silt (grain size mainly between 0.005 and 0.05 mm, and water content of 26 to 29%), Tsytovich (1975) found that under a pressure of 200 kPa, the variation of Young's modulus E with temperature could be represented by the empirical equation: $E=400(1+3.5\theta)$.

Therefore, although frozen soils are usually considered to be practically incompressible, the compressibility plays an important role in the experiments. During the experiments, the loads applied were not maintained for a long period of time and the time-dependent deformation was not considered. In general, compressibility in frozen soils are due to several causes, such as instantaneous compression of the gaseous phase, creep of ice cement at the grain contacts, and hydrodynamics consolidation due to the expulsion under stress of unfrozen water. All the causes could make the frozen soils tighter and prevent the development of the fracture in frozen soils. It was found that applying loads could decrease the permeability from 10% to 30% depending on two other factors, temperature and moisture content. In Figures 4.3.13 and 4.3.14, the 50 psi applied load reduces the permeability of the soil samples with different moisture contents.

In the laboratory studies, several experiments were conducted to test the effect of the increasing loads varying from 0 psi to 50 psi with increments of 5 to 10 psi. The results indicated that, the applied load had less significant effect as compared to the other factors (moisture content and temperature). Another finding is that the applied load had a slightly more significant impact on the permeability when the moisture content was low. The lower moisture content the soil has, the lower degree of saturation and bulk density it is. Therefore, under the applied loads, there is more room in soil to compress causing more significant effect on the permeability change.

4.3.5 The Experiments Errors

During the experiments, the errors were not avoidable. There could be several sources of the errors:

1. The equipment error. (1) Although the gas leakage from the experiment system was minimized to ensure accurate measurement, the leakage was still possible. That became a possible source of error in the experiments. (2) Gas permeameter could also have equipment error. (3) The hydraulic loading system could not control the loads precisely because of the low load used in the study as compared with the capacity of the loading system and it was difficult to maintain the low loads with the change of the temperature.

2. The measurement error. (1) The water temperature in the cooling coil system was measured and considered to be approximately the same as that inside the soil sample. Although the measurement was taken until the temperature reached its equilibrium or near equilibrium point, some small error cannot be avoided because it was found that the water temperature was slightly different at different depths. (2) The reading of gas permeameter did not keep stable in the measurement. An average reading was taken as the result in the experiments. (3) The length of the soil sample was measured before it was tested and was considered as the length of the sample during the testing. Actually, the length of the soil sample changed a bit as the temperature changed. In addition, the applied loads could change the sample length. That was another possible source of error in the experiments. (4) As mentioned in 4.1, the specially designed device for very low permeability measurements has also some possible errors in the measurement.

Chapter 5

Conclusion and Recommendations

5.1 Conclusions

Based on the laboratory experiment results from this study, the following conclusions can be drawn:

1. Moisture/ice content was found to be the most significant factor that had a great impact on the gas permeability of frozen soils. The physical behavior of frozen soils depends, to a great degree, on the pore ice existence in frozen soils. When ice fills most of the pore space, as temperature drops, the behavior of frozen soil will reflect closely to that of the ice whose gas permeability approaches zero. The higher moisture content the soil has, the more water freezes at low temperature. The more pore ice binds the grains together and fills the pore space, the more difficult the gas flows through the soil sample, resulting in lower permeability in the soil sample. Therefore, the moisture/ice content has the most significant effect on gas permeability.

   Higher permeability was observed as the temperature dropped below 20°F. One explanation for this observation was that the bound water began to freeze at this temperature and the soil particles expanded due to bound water freezing. The expanded soil particles reduced the specific surface area of the soil, thus higher permeability. A second explanation was that the water filming on the soil particles changed to ice at 20°F and expanded its volume. This expansion of volume might caused the development of micro-fractures, resulting higher permeability. However, no concrete conclusion can be drawn at this point from this observation. Further and more in-depth study is needed.

2. It was found that there was a transition zone for frozen soil to behavior differently over temperature. Based on the experiment results, the zone could be around 10% of moisture content. With moisture content less than this level, the unfrozen water froze faster and the pore ice filled the space faster. This resulted a greater change of permeability over temperature. When the moisture content was more than the level, the rate of freezing and pore icing was lower, causing a smaller change of permeability over temperature.

3. During the experiments, applying loads reduced permeability by 10% to 30% depending on three factors (temperature, moisture content and applied loads). The applied loads can make the frozen soils tighter because of the compressibility in frozen soils. In addition, the load could prevent or limit the development of micro-factures in the soil samples. Another finding was that the load had a little more effect on the permeability at lower moisture content. This is likely due to the fact that soil samples with lower moisture content has more void room in the soil to compress, and therefore, the effect of the applied loads is more significant.

4. The effect of temperature on gas permeability in frozen soil was found less significant than that of moisture content. However, because most of the soil samples tested in this study had less than 20% of moisture content, the soil whose moisture content is much greater than 20% may have different characteristics. There may be other transition zones, similar to the one found around 10% of moisture content, over a greater range of moisture contents.

When the moisture content is in a much higher range, the effect of temperature may be more significant than that found in this study.

5.2 Recommended Future Work

The experiment is a preliminary study on gas permeability of frozen soil. Based on the results of this preliminary study, more in-depth investigations on gas permeability of frozen soil are suggested below.

1. Improvement of the equipments for higher accuracy measurement of the gas permeability. During the experiment, the accuracy of the equipment was not particularly high. Improvement in measurement accuracy will possibly provide better understanding of the characteristics of gas dissemination in frozen ground and may result in new or improved conclusions

2. Measurement of the gas permeability of the soil samples with more than 30% and up to 100% moisture content. From the basic properties of soil, the liquid limit is about 30%. The soil with more than 30% moisture content may have a very different physical behavior as compared to that with less moisture content. In addition, it is not uncommon to find soil with more than 50% of moisture content, particularly in Fairbanks, Alaska. The measurement of the higher moisture content soil will help study the gas dissemination in frozen ground with higher moisture content.

3. Detailed observation of the sample's interior to study the microstructure of the soil sample. The change of the microstructure of soil with temperature,

moisture content or other factors causes the change of the gas permeability. The observation of the samples can play an important role in the research.

4. Mathematical modeling study to simulate gas dissemination in frozen ground. Three-dimensional models will provide a more realistic representation of engineering problems, although it takes longer time to develop and require more computer resources. The commercially available software such as ABAQUS, can be used to simulate the gas dissemination in frozen ground.

5. It is recommended that gas slippage be measured for in-depth investigation of the characteristics of gas dissemination in frozen ground. The gases display a permeability value that depends on not only the media, but also the identity of the gas and the pressure differential across the media. The estimation of the effect of the gas slippage will provide a more accurate prediction of gas movement behavior in frozen ground.

Reference

American Association of State Highway and Transportation Officials: Standard Specifications for Transportation Materials and Methods of Sampling and Testing Part 2 – Test, (2001), AASHTO.

American Society for Testing and Materials: 1994 Annual Book of ASTM (Section 4 Construction), (1994), ASTM.

Andersland, O. B. and Ladanyi, B.: An Introduction to Frozen Ground Engineering, (1994), Chapman & Hall, Inc.

Andersland, O. B. and Anderson, M.A.: Geotechnical Engineering for Cold Regions, (1978), McGraw-Hill Book Company.

Anderson, D.M. and Morgenstern, N.R.: "Physics, Chemistry and Mechanics of Frozen Ground: A Review", Proc. 2nd International Conference on Permafrost, Yakutsk, U.S.S.R., North American Contribution, U.S. National Academy of Science, (1973), pp. 257-288.

Benoit, G.R. and Bornstein, J.: "Freezing and Thawing Effects on drainage", Proceedings of Soil Science Society Annual Meeting, (1970), 34 (4), pp. 551-557.

Brown, W.G.: "Graphical Determination of Temperature under Heated or Cooled Areas on the Ground Surface", (1963), Natl. Res. Council. Can. Div. Build. Res. Tech. Pap. 163.

Budhu, M.: Soil Mechanics and Foundations, (2000), John Wiley & Sons, Inc.

Campbell, D.J.M.: Petroleum Reservoir Property Evaluation, (1993), John M. Campbell and CO.

Chamberlain, E.J. and Gow, A.J.: "Effect of Freezing and Thawing on the Permeability and Strucure of Soils", Engineering Geology, (1978), 13, pp. 73-92.

Chierici, G.L.: Principles of Petroleum Reservoir Engineering, (1995), Springer-Verlag.

Counsil, J.R.: "Steam-Water Relative Permeability", Ph.D. Dissertation, (1979), Stanford University.

Das, B. M.: Soil Mechanics Laboratory Manual, (1997), Engineering Press

Ertekin, T., Abou-Kassem, J.H. and King, G.: Basic Applied Reservoir Simulation, (2001), Society of Petroleum Engineers.

Fang, H.Y.: Foundation Engineering Handbook, (1991), Van Nostrand Reinhold.

Freeze, R. A. and Cherry, J. A.: Groundwater, (1979), Prentice Hall

Gopalsami, N. and Raptis, A.C.: "Microwave Radar Sensing of Gas Pipeline Leaks", Final Report of Argonne National Laboratory, (2002).

Hofmann, J. R. and Hofmann, P. A.: "Darcy's Law and Structural Explanation in Hydrology", Proceedings of the 1992 Biennial Meeting of the Philosophy of Science Association, volume 1. (1992), pp. 23-35.

Hubbert, M. K.: The Theory of Groundwater Motion and Related Papers, (1969), Hafner Publishing Company

Johnston, G.H.: Permafrost Engineering Design and Construction, (1981), John Wiley & Sons, Inc.

Jones, F.O. and Owens, W.W.: "A Laboratory Study of Low-Permeability Gas Sands", Journal of Petroleum Technology, (1980), September, pp.1631-1640.

Jumikis, A.R.: Thermal Geotechnics, (1977), Rutger, the State University of New Jersey.

Kentfield, J. A. C.: Non-steady, One-Dimensional, Internal, Compressible Flows (Theory and Applications), (1993), Oxford University Press.

Klinkenberg, L.J.: "The Permeability of Porous Media to Liquids and Gases", Drill. and Prod. Prac., (1941), pp. 200-213.

Konrad, J.-M.: " Effect of Freeze-Thaw Cycles on the Freezing Characteristics of A Clayey Silt at Various Overconsolidation Ratio", Can. Geotch. Journal, (1989), Vol. 26, pp. 217-226.

Konrad, J.-M.: " Physical Processes During Freeze-Thaw Cycles in Clayey Silts", Cold Regions Science and Technology, (1989), Vol. 16, pp. 291-303.

Li, K. and Horne, R. N.: "Gas Slippage in Two Phase Flow and the Effect of Temperature", SPE 68778, Proceedings of the 2001 SPE Western Region Meeting, Bakersfield, CA, USA, March 26-30, 2001.

Linell, K.A. and Kaplar, C.W.: Description and Classification of Frozen Soils, U.S. Army Cold Reg. Res. Eng. Lab. Tech. Rep. 150. (1966), Hanover, N.H.

Lunardini, V.J.: Heat Transfer in Cold Climates, (1981), Van Nostrand Reinhold.

Porkhaev, G.V.: "Some Data on the Permeability Coefficient of Thawing ground", Mater. Lab. Issled. Merzlykh Gruntoved. Sb., (1961) 4: pp. 100-103.

Rice, E.: Building in the North, (1996), Alaska Science & Technology Foundation.

Sampath, K. and Keighin, C.W.: "Factors Affecting Gas Slippage in Tight Sandstones of Cretaceous Age in the Uinta Basin", Journal of Petroleum Technology, (1982), November, pp. 2715-2720.

Shrader-Frechette, K. S. "Idealized Laws, Antirealism, and Applied Science: A Case in Hydrogeology", (1989), Synthese 81: 329-352

Smith, L.B.: Thaw Consolidation Tests on Remolded clays, Unpublished M. Sc. Thesis, (1972), Univ. Alberta, Edmonton.

Smoltczyk, U.: Geotechnical Engineering Handbook, (2002), Ernst & Sohn.

Terzaghi, K. and Peck, R.: Soil Mechanics in Engineering Practice, (1996), John Wiley & Sons, Inc.

Thomas, R.D. and Ward, D.C.: "Effect of Overburden Pressure and Water on Gas Permeability of Tight Sandstone Cores", Journal of Petroleum Technology, (1972), February, pp.120-124.

Tice, A.R., Anderson, D.M. and Banin, A.: The Prediction of Unfrozen Water Contents in Frozen Soils from Liquid Limit Determination, (1976), U.S. Army Cold Reg. Res. Eng. Lab. CRREL Rep. 76-8.

Torsaeter, O. and Abtahi, M.: Experimental Reservoir Engineering Laboratory Work Book, (2000), Norwegian University of Science and Technology.

Tsytovich, H. A.: The Mechanics of Frozen Ground (trans), eds. G. K. Swinzow and G. P. Tshebotarioff, (1975), New York: Scripta/McGraw-Hill.

U.S.S.R.: Handbook for the Design of Bases and Foundations of Buildings and Other Structures on Permafrost, (1969), Canada, National Research Council, Tech. Transl. TT 1865, pp. 129.

Wendt, J F.: Computational Fluid Dynamics An introduction, (1992), Springer-Verlag.

Zucrow, M. J. and Hoffman, J. D.: Gas Dynamics Volume I, (1976), John Wiley & Sons.

Appendix

The Original Data

Table A.1 Moisture Content was 5.8%

Moisture Content	Length of the sample (in)
5.8%	1.023

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
25	102			50	0.3923
19	102			50	0.3885
8	112			50	0.3883
0	136			50	0.5271
-10	158			50	0.6870
-10	158			50(*)	0.6870
-10	158			100	0.6870
-10	158			200	0.6870

* shows the 50 psi load was released and re-applied on the sample

Table A.2 Moisture Content was 8.8%

Moisture Content	Length of the sample (in)
8.8%	1.181

Temperature(F)	Reading of Gas Permeameter			Load (psi)	permeability (Darcy)
	Large	Medium	Small		
28	57			0	0.2371
24	57			0	0.2355
20	64			0	0.2711
15	70			0	0.3004
15	51			50	0.2055
10	52			50	0.2090
4	54			50	0.2177
11	49			50	0.1887
27	46			50	0.1778

Table A.3 Moisture Content was 9.9%

Moisture Content	Length of the sample (in)
9.9%	1.183

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
24	27	110		50	0.0945
18	25	103		50	0.0914
9	25.5	106		50	0.0910
9	25	103		50	0.0900
5	25.5	107		50	0.0905

Table A.4 Moisture Content was 10.0%

Moisture Content	Length of the sample (in)
10.0%	1.040

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
24	44			0	0.1510
20	41			0	0.1397
15	43			0	0.1469
10	55			0	0.1935
4	62			0	0.2227
0	64			0	0.2316

Table A.5 Moisture Content was 10.0% (The sample was thawed and refrozen)

Moisture Content	Length of the sample (in)
10.0%	1.040

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
28	51			0	0.1853
24	45			0	0.1558
20	48			0	0.1688
15	57			0	0.2045
10	69			0	0.2534
4	82			0	0.3058

Table A.6 Moisture Content was 10.0% (This sample is a different one from the above.)

Moisture Content	Length of the sample (in)
10.0%	1.082

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
29	40			50	0.1436
21	36			50	0.1240
15	36			50	0.1228
7	38			50	0.1288

Table A.7 Moisture Content was 11.7%

Moisture Content	Length of the sample (in)
11.7%	1.000

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
29	35	150		50	0.1144
25	33	140		50	0.1045
17	32	134		50	0.0986
9	36	155		50	0.1150
2	40			50	0.1323

Table A.8 Moisture Content was 11.7% (The sample was thawed and refrozen)

Moisture Content	Length of the sample (in)
11.7%	1.000

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
26	34	148		50	0.1093
21	33	140		50	0.1038
10	40			50	0.1285
5	44			50	0.1407
-1	50			50	0.1656

Table A.9 Moisture Content was 12.7%

Moisture Content	Length of the sample (in)
12.7%	1.082

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
28	51			0	0.1928
24	52			0	0.1964
20	50			0	0.1853
15	58			0	0.2224
9	87			0	0.3445
6	101			0	0.4001

Table A.10 Moisture Content was 12.7% (The sample was thawed and refrozen)

Moisture Content	Length of the sample (in)
12.7%	1.082

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
28	34			0	0.1186
24	34			0	0.1179
20	31			0	0.1024
15	42			0	0.1499
10	53			0	0.1965
15	25			50	0.0795
10	26	108		50	0.0824
9	26			50 (*)	0.0823
5	28	118		50	0.0909
-1	31			50	0.0990

* shows the 50 psi load was released and re-applied on the sample

Table A.11 Moisture Content was 19.5%

Moisture Content	Length of the sample (in)
19.5%	0.963

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
28			49	0	0.0028
10			44	0	0.0026
5		32	153	0	0.0150
0	12	45		0	0.0247

Table A.12 Moisture Content was 19.5% (The sample was thawed and refrozen)

Moisture Content	Length of the sample (in)
19.5%	0.944

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
27			47	0	0.0027
20			55	0	0.0031
15			92	0	0.0060
10		37		0	0.0172
5		53		0	0.0310
0	18	76		0	0.0517

Table A.13 Moisture Content was 5.5%

Moisture Content	Length of the sample (in)
5.5%	1.017

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
11	92			0	0.3431
11	91			5	0.3385
11	90			11.7	0.3340
11	85			21.7	0.3160
11	85			31.9	0.3160
11	81			40.7	0.2979
11	81			47.4	0.2979

Table A.14 Moisture Content was 13.9%

Moisture Content	Length of the sample (in)
13.9%	1.222

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
7	97			0	0.4363
7	95			5	0.4255
7	92			11.7	0.4094
7	85			21.7	0.3770
7	73			31.9	0.3178
7	73			40.7	0.3178
7	71			47.4	0.3070

Table A.15 Moisture Content was 17.6%

Moisture Content	Length of the sample (in)
17.6%	1.089

Temperature(F)	Reading of Gas Permeameter			Load (Psi)	permeability (Darcy)
	Large	Medium	Small		
11	33			0	0.1112
11	36			5	0.1257
11	34			11.7	0.1160
11	33			21.7	0.1112
11	33			31.9	0.1112
11	32			47.4	0.1063

Table A.16 Moisture Content was 23.8%

Moisture Content	Length of the sample (in)	Load (Psi)
23.8%	1.182	0

Temperature(F)	permeability (Darcy)	Flow rate (cm3/sec)
25	9.2442E-05	0.00861323
20	4.16964E-05	0.003916161
15	5.04457E-05	0.004779124
11	5.69265E-05	0.005430223

Table A.17 Moisture Content was 25.0%

Moisture Content	Length of the sample (in)	Load (Psi)
25.0%	1.181	0

Temperature(F)	permeability (Darcy)	Flow rate (cm3/sec)
25	3.73786E-05	0.003482729
19	4.68019E-05	0.004403812
14	6.31553E-05	0.005994377